ARSENIC TREATABILITY OPTIONS AND EVALUATION OF RESIDUALS MANAGEMENT ISSUES

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FOREWORD

Chiang, Patel & Yerby, Inc. (CP&Y), is pleased to submit the report "Arsenic Treatability Option and Evaluation of Residuals Management Issues" according to Contract No. C-14339.

This report includes results of many hard months of hard working team co-workers under the leadership of the City of Fort Worth's Mr. Jim Scanlan and Mr. Richard S. Talley, and CP&Y's project manager, Edward M. Motley. Our special thanks to Dr. Syed Qasim of The University of Texas at Arlington, as his vision and inspiration have contributed greatly to this project.

A significant portion of the work presented in this report was performed by the Department of Civil and Environmental Engineering and the Department of Chemistry and Biochemistry at the University of Texas at Arlington, Texas (UTA), under a contract from Chiang, Patel and Yerby, Inc. The report contains the findings of one year of bench-scale reactor studies on enhanced coagulation and on utilization of electrotechnologies for arsenic and TOC removal from municipal water supplies. Dr. Syed R. Qasim, professor of civil and environmental engineering, and Dr. K. Rajeshwar, professor of chemistry and biochemistry, were the principal investigators. Personnel and organizations that assisted on the project and their representatives are listed below.

Mr. Guang Zhu of UTA conducted jar tests and data analysis on enhanced coagulation studies. He also prepared the draft copy of the quarterly and final reports. Mr. M. Kamal and Mr. W. Lee of UTA assisted with coagulation experiments. Mr. H. Young and Mr. W. Lin of UTA conducted photocatalytic oxidation studies.

The enhanced coagulation studies were conducted at the pilot plant facility at the Rolling Hills Water Treatment Plant (RHWTP) in Fort Worth, Texas. The RHWTP provided support services and coordinated the sample delivery and data acquisition. Also, the water quality laboratory at RHWTP performed UV254 and total THM measurements. Inchcape Testing Services was retained to conduct total and dissolved arsenic and TOC and DOC measurements.

Mr. John Marler of CP&Y conducted the pilot plant studies. He operated the pilot plant, collected samples, analyzed field tests, and coordinated laboratory analyses with the RHWTP and a commercial testing service. He also prepared the pilot plant study section of this report. Mr. Marler's dedication, shown by his working both day and night at the pilot plant, is highly appreciated.

Thanks also go to Mr. Paul L. Wolske of TU Electric for providing ozone operating cost data for U.S. water treatment plants. These data have been included in this report.

The Texas Natural Resource Conservation Commission (TNRCC) provided the arsenic data on surface water sources in Texas. Mr. G. Johnson of CP&Y plotted the arsenic concentration profiles on a Texas map. The Tarrant County Water Control and Improvement District No. 1 (TCWCID No. 1) provided arsenic data and water quality and flow information about the Cedar Creek and Richland Chambers Reservoirs. The City of Arlington supplied samples of alum coagulant and shared arsenic removal data. Freese and Nichols, Inc., loaned the ozone generator and supplied ozonation information.

EXECUTIVE SUMMARY

The arsenic level in drinking water has received much attention in recent years. Information on the health risks caused by arsenic is expected to drive the current standard of 50 μg/L down to 5 μg/L or less. Also, the Disinfectant - Disinfection Byproduct Rule (D-DBR) will force the utilities to balance the benefits of disinfection against the undesirable by-products. Ozonation is being considered nationwide to enhance disinfection without the use of chlorine. A research program was conducted to address the issues of arsenic and natural organic matter (NOM) removal.

The objectives of this study are to evaluate the technologies for removal of low-level arsenic from drinking water. Bench-scale and pilot studies were conducted to investigate arsenic and NOM removals by utilization of modified coagulation processes and use of electrotechnologies. Major research efforts were devoted to the following issues: occurrence of arsenic in surface water sources in Texas, a bench-scale study on enhanced coagulation and advanced photocatalytic technologies, a pilot plant study for arsenic removal, and data projection for full-scale plant operation.

ES1 OCCURRENCE OF ARSENIC IN SURFACE WATER SOURCES IN TEXAS

The State of Texas has an ambitious water quality monitoring program to characterize existing water quality problems and develop long-term solutions. A large number of organic and inorganic constituents are monitored on a routine basis. Total arsenic is one of the constituents tested. The Texas Natural Resource Conservation Commission (TNRCC) records indicate that the concentration of arsenic in most surface water sources in Texas is less than 20 μg/L. Only a few hot spots in Texas show a total arsenic concentration exceeding 30 μg/L.

ES2 BENCH-SCALE STUDY ON ENHANCED COAGULATION

A number of bench-scale coagulation experiments were conducted with standard jar test apparatus. The experimental data obtained from 45 jar tests were used to (1) develop coagulation diagrams, (2) assess the effect of preozonation on arsenic removal, (3) estimate the sludge production rate and arsenic concentration in the sludge, and (4) develop an arsenic removal mechanism.

ES2.1 COAGULATION DIAGRAMS

Coagulation diagrams provide a graphic representation of the removal behavior of the targeted constituents in coagulated and settled water. The targeted constituents used in this study are (1) turbidity, (2) arsenic, (3) organic carbon, and (4) absorbance at UV254 nm. Each diagram represents the removal of a constituent as a function of final pH value and coagulant dosage.

Twenty-one jar tests were conducted with arsenic-spiked raw lake water samples. Initial total arsenic concentrations in the raw water after spiking were in the range of 10 - 20 μg/L. Ferric sulfate, ferric chloride, and alum were used as primary coagulants in each test. Sulfuric acid, sodium hydroxide, and lime were used to adjust the final pH in the settled water to cover the targeted range of pH 5 - 10.

Coagulation diagrams were completed for both ferric sulfate and ferric chloride. The generalized best and worst operational conditions for each coagulant are summarized in Table ES-1 and ES-2, respectively.

Alum coagulation results were obtained for only two pH levels. The coagulation with alum follows the same trends as those with iron-based coagulants in removing the targeted constituents. The data were not sufficient to develop a coagulation diagram. The general trend is (1) better removals for both turbidity and total arsenic near natural pH, (2) poor TOC removal with alum, and (3) some reduction in UV254 absorbance at lower pH values.

TABLE ES-1
SUMMARY OF OPERATIONAL CONDITIONS FOR COAGULATION WITH FERRIC SULFATE OR FERRIC CHLORIDE

OBJECTIVE	COAGULANT	BEST CONDITIONS	WORST CONDITIONS
Removal of Turbidity	$Fe_2(SO_4)_3$	pH 4.5 and 8.5 with optimum Fe(III) dosage of 8 mg/L	pH 6 - 7
	$FeCl_3$	pH 8 - 8.5 with optimum Fe(III) dosage of 6 mg/L	pH 6 - 6.5
Removal of Total Arsenic	$Fe_2(SO_4)_3$	pH 4.5 and 8.5 - 9 with optimum Fe(III) dosage of 6 mg/L	pH 6 - 7.5
	$FeCl_3$	pH 8 - 8.5 with optimum Fe(III) dosage of 6 mg/L	pH 6 - 6.5
Removal of Dissolved Arsenic	$Fe_2(SO_4)_3$	No influence of pH if Fe(III) dosage is higher than 6 mg/L	pH 8 - 9.5
	$FeCl_3$	N/A	N/A
Removal of TOC	$Fe_2(SO_4)_3$	pH < 6.5 with optimum Fe(III) dosage of 8 mg/L	pH 7.5 - 9
	$FeCl_3$	pH < 6.5 with optimum Fe(III) dosage of 14 mg/L	pH > 7.5
Reduction in UV 254 Absorbance	$Fe_2(SO_4)_3$	pH < 6 with optimum Fe(III) dosage of 8 mg/L	pH 7.5 - 9
	$FeCl_3$	pH < 6 and 9 - 9.5 with optimum Fe(III) dosage of 6 mg/L	pH 7 - 8.5

ES2.2 PREOZONATION

Seven jar tests were conducted with and without preozonation. Both As(III)- and As(V)-spiked raw water samples were coagulated using ferric chloride and ferric sulfate. No pH adjustment was used in the preozonation experiments.

Total arsenic removal in As(III)- and As(V)-spiked water samples without preozonation were 65 - 80 and 90 - 95 percent, respectively, at an Fe(III) dosage over 8.4 mg/L. The As(III) removal, however, increased significantly after preozonation. This increased removal was in the range of 90 - 95 percent and approached the removal value of As(V)-spiked water without preozonation.

The improvement in As(III) removal after preozonation is a clear indication of complete conversion of As(III) into As(V) due to oxidation. The experimental data also show that total arsenic removal is improved at lower Fe(III) dosages following preozonation. This may be due to enhanced turbidity removal. Ferric chloride coagulation after preozonation was much more effective for As(III) and turbidity removals than was ferric sulfate.

ES2.3 SLUDGE PRODUCTION AND ARSENIC CONCENTRATION IN SLUDGE

Six jar tests were conducted to develop the sludge quantity production data. Raw water samples without arsenic spiking were coagulated with ferric chloride and ferric sulfate. A linear relationship between the total amount of sludge mass produced and the amount of Fe(III) applied was noted. The sludge volume showed a nonlinear relationship with respect to the amount of Fe(III) applied. A generalized equation is developed for estimating the arsenic concentration in sludge. The arsenic concentration in sludge produced from conventional coagulation will be considerably higher than that with enhanced coagulation for the same arsenic level in raw water. This is a significant finding. A possible explanation of this trend is a high arsenic removal rate at a lower coagulant dose. As the coagulant dosage is increased, the sludge quality is improved significantly by reducing the arsenic concentration in the sludge.

ES2.4 ARSENIC REMOVAL MECHANISM

Eleven jar tests were conducted to study the arsenic removal mechanism. Arsenic-spiked tap water samples were utilized in the experiments with ferric chloride coagulation. The effect of initial turbidity on arsenic removal was studied by the use of artificial turbidity. Kaolin powder, a clay-based material, was used to create the desired level of initial turbidity.

The removal of arsenic by coagulation occurs in two steps. Step 1 is an immobilization process in which soluble arsenic is converted into particulate arsenic, and Step 2 is a separation process in which the particulate arsenic is removed from the aqueous system. The overall arsenic removal efficiency is affected by both steps. Even at 50 μg/L initial dissolved As(V) concentration in raw water, an arsenic level of less than 2 μg/L can be achieved in the finished water at an Fe(III) dosage of 4 mg/L, provided that the turbidity in coagulated water is effectively removed.

ES3 BENCH-SCALE STUDY OF ADVANCED PHOTOCATALYTIC TECHNOLOGIES

In this study, two new technologies for improving the removal of As(III) were demonstrated by the proof-of-concept experiments. The first technology is based on photocatalytic oxidation of As(III) to As(V), and the second method utilizes photocatalytic reduction of As(III) to As(0). The second method has an added process advantage because the arsenic is immobilized and sequestered from the water.

Ultraviolet (UV) radiation in conjunction with hydrogen peroxide (H_2O_2) and titanium oxide (TiO_2) is very effective for oxidation of As(III) to As(V). The ratio of As(III) to As(V) was monitored as a function of treatment time by ion chromatography. Hydrogen peroxide also oxidized As(III) in the dark, but the oxidation state was much slower than when radiation was used. The feasibility of using Fe(II) ions in conjunction with UV/TiO_2 to immobilize arsenic as $FeAsO_4$ remains inconclusive because of analytical problems.

In this method, photocatalytic reduction of As(III) to As(0) onto the TiO_2 surface is involved. The concentration of dissolved arsenic in the water samples was monitored as a function of TiO_2 irradiation time by a UV-visible spectrophotometric method. The preliminary results are very encouraging.

ES4 PILOT PLANT STUDIES FOR ARSENIC REMOVAL

In the pilot plant studies, thirty-three tests were conducted to confirm the findings of the bench-scale studies and to further investigate the effects of utilization of different types of coagulants, cationic polymer, and preozonation on arsenic removal. The results of these studies were utilized to project full-scale plant operation.

Eleven pilot-scale tests with ferric sulfate as the solo primary coagulant were conducted to verify the results of bench-scale experiments. The results show that the removal of turbidity, total arsenic, and TOC in settled water were generally consistent with those described in the coagulation diagrams developed in the bench-scale jar test experiments. At an Fe(III) dose of 6.3 mg/L and a pH below 9.5, the results of pilot-scale tests indicated that there were no significant effects of pH on total arsenic removal after filtration. At a pH above 9.5, however, filtration was not very effective in removing arsenic from settled water.

To compare the effectiveness of arsenic removal with ferric sulfate and ferric chloride, a few pilot tests were conducted with a ferric chloride coagulant. At a pH approximately 8.0 - 8.7 and at an Fe(III) dosage of 6.3 mg/L, the results show that a slightly higher removal of total arsenic in settled water was observed with ferric chloride coagulation. However, there were no significant differences in total arsenic residuals in the filtered water after coagulation with ferric sulfate and ferric chloride.

Several pilot-scale tests were conducted to evaluate the effect of utilization of cationic polymer on the removal of arsenic. The results show that the removal of turbidity in settled water was improved by the addition of polymer. The removal of total arsenic, therefore, was also enhanced. However, there were no significant changes in total arsenic residuals between the filtered water samples with and without addition of polymer.

Several pilot plant tests were conducted with both As(V)- and As(III)-spiked water samples in preozonation studies. The results of tests without preozonation indicated that As(III) was harder to remove than AS(V). After preozonation, however, the removal trends of total arsenic with As(III)-spiked samples were the same as those with As(V)-spiked samples. The results of the tests with As(V)-spiked samples after preozonation also showed that the removal trends were similar to those with the addition of polymer.

ES5 PROJECTED ENERGY CONSUMPTION DUE TO INCREASED OZONATION PRACTICE IN MUNICIPAL WATER TREATMENT

An overview of the ozonation technologies used in water treatment practice indicated that ozonation water treatment is on the rise in the U.S. More than 150 water treatment systems are projected to have ozonation facility on line by 1998. Based on the data from both national and local applications of ozone in water treatment, it is projected that by the year 2000 , the following will have occurred:

- The total capacity of water treatment plants with ozonation will reach 5.5 billion gallons per day, serving a population of 33.2 million.
- A total ozone usage of 100,000 lb per day will be reached.
- A total energy demand of 1.26 million kWh per day will be imposed by the ozonation facilities. The added cost of energy for ozonation facilities will be $18 per million gallons of water treated.

ES6 DATA PROJECTION FOR FULL-SCALE PLANT OPERATION

Based on the data obtained in the bench-scale and pilot-plant experiments, the options of full-scale operation to remove arsenic and TOC have been assessed.

The options of full-scale operation to meet requirements of (1) an arsenic concentration of less than 5 μg/L in finished water, and (2) approximately 30 percent TOC removal were evaluated under three raw water quality conditions. The impacts of these options on operational cost are summarized in Table ES-3. The increase in treatment costs corresponding to these options is also projected.

TABLE ES-2

IMPACTS OF OPERATIONAL OPTIONS ON COST CHANGE

Option Code	Raw Water Condition	Treatment Process Options	Cost Change		
			Energy Demand	Additional Chemical Dosage	Additional Residue Management
I	I	CC	0	0	0
II-1	II	EC	0	++	++
II-2		PO+CC	+++	0	0
III-1	III	EC	0	+++	+++
III-2		PO+EC	+++	+	+

Note: 1. Raw water conditions:

I - initial arsenic concentration of 4 - 6 μg/L
II - initial arsenic concentration of 30 μg/L
III - initial arsenic concentration of 50 - 100 μg/L

2. Treatment process options:

CC - conventional (existing) coagulation process with Fe(III) dosage of 3 mg/L
EC - enhanced coagulation process with Fe(III) dosages of 4.5 - 9 mg/L
PO - preozonation process with ozone dosage of 2.5 mg/L

3. Cost changes:

0 - no changes
+ - slightly increase
++ - moderate increase
+++ - significant increase

Chapter 1
INTRODUCTION

1.1 ARSENIC PROBLEMS AND RESEARCH NEEDS

The potential toxic effects of arsenic on humans have been investigated in the United States, Taiwan, Mexico, India, Chile, and Japan. The International Agency for Research on Cancer (IARC) (1980) has shown that ingestion of inorganic arsenic can cause cancer of the skin and vital internal organs such as the liver, lungs, kidneys, and bladder. The National Research Council of Canada (1978) reported that the possible mechanisms are inhibition of replication, interruption of repairing functions and blockage of DNA, and a variety of enzyme complexes.

In the United States, the information on the health risks associated with arsenic is expected to drive the current total arsenic standard of 50 μg/L down to 5 μg or less. Also, the Disinfectants and Disinfection By-Products (D-DBP) Rule will force the utilities to balance the benefits of disinfection against the undesirable by-products. As a result, removal of natural organic matter (NOM) must be optimized. These regulations will impose billions of dollars of additional compliance costs on water utilities (Pontius 1995b).

A research program was conducted to address the issues of arsenic and NOM removal from surface water supply sources by utilization of modified coagulation and use of electrotechnologies for removal of arsenic and NOM from municipal surface water supply sources.

1.2 OBJECTIVES

This study had several purposes:

- Develop data on the occurrence of arsenic in surface water sources in Texas.

- Conduct bench-scale enhanced coagulation studies and utilize preozonation and alternative electrotechnology for removal of arsenic and TOC.

- Conduct pilot plant studies with and without preozonation, and assess arsenic and TOC removals.

- Project the results of bench and pilot plant studies to establish full-scale treatment plant performance with enhanced coagulation, energy balance of preozonation, and residuals management options.

1.3 RESEARCH SUPPORT AND ACTIVITY

This research program was supported by funds from the Texas Water Development Board, the Electric Power Research Institute/TU Electric, and the City of Fort Worth, Texas. The research program was conducted at the pilot plant facility at the Rolling Hills Water Treatment Plant (RHWTP) in Fort Worth, Texas. This program was conducted and coordinated by Chiang, Patel & Yerby, Inc. Research support was provided by the Department of Civil and Environmental Engineering and the Department of Chemistry and Biochemistry at The University of Texas at Arlington.

Bench-scale studies were conducted by the Department of Civil and Environmental Engineering and the Department of Chemistry and Biochemistry at The University of Texas at Arlington. Pilot plant studies were conducted by Chiang, Patel & Yerby, Inc. Arsenic data on surface water sources in Texas were provided by the Texas Natural Resource Conservation Commission (TNRCC), the Tarrant County Water Control and Improvement District No. 1 (TCWCID No. 1), and the City of Arlington, Texas.

1.4 REPORT FORMAT

This report contains the results of bench-scale investigations. The background information, major findings, conclusions, and recommendations are contained in the main body of this report.

Experimental procedures, experimental results, and supporting technical information are provided in Appendices A through F.

Chapter 2
BACKGROUND

2.1 BASIC CHEMISTRY OF ARSENIC

Arsenic can occur in four oxidation states in water [+V (arsenate), +III (arsenite), O (arsenic), and -III (arsine)], but is generally found in only the trivalent and pentavalent states. The oxidation state of arsenic and the pH of the aqueous media influence the predominance of As(III) and As(V). In well-aerated surface waters, arsenic species should be in the arsenate [As(V)] forms. Mildly reducing conditions, such as those that can be found in bottom mud in lakes and well water, should produce arsenite [As(III)]. Arsenic trioxide (H_3AsO_3), an undissociated weak acid, is predominant in the pH range of 2-9; therefore, any As(III) present in a typical water supply would occur as H_3AsO_3. As(V) will occur as a strong acid and dissociates in different pH ranges. H_4AsO^{-2} predominates from pH 7 to pH 11.5, indicating that this would most likely occur in normal water supplies. At a pH of less than 7, $H_2AsO^{-2}{}_4$ dominates (James Montgomery, 1985).

2.2 OCCURRENCE OF ARSENIC IN NATURAL WATERS

Sources of arsenic in an aquatic environment are the result of both natural and human activities. Leaching of arsenic-rich soils and minerals can cause elevated levels of arsenic in groundwater and seepage-fed surface waters. The influence of human activity on the amounts of arsenic in surface waters is significant. Some of these activities and sources are production and use of some agricultural pesticides, phosphate-containing fertilizers, smelting or roasting of many sulfide-containing minerals, combustion of fossil fuels, making of colored glass and metal alloys, and leaching of mining ore and fly ash (Ferguson and Gavis 1972; Davenport and Peryea 1991; and Peryea 1991).

Arsenic surveys about drinking water supplies conducted in 1943 and 1969 indicated an increase in the mean arsenic level in United States water supplies (Ferguson and Gavis 1972). Arsenic in aquatic systems has a complex chemistry, including oxidation reduction, ligand exchange, precipitation, and adsorption reactions. In lakes, the arsenic reactions include transfers from a solution to a solid phase, and conversion from one oxidation state to another by chemical and microbial activity. Under aerobic conditions, arsenic is oxidized to arsenate, which coprecipitates with ferric hydroxide. Under anaerobic conditions, microbial reduction solubilizes the arsenic and its diffusion through the sediments, or mixing by currents. These phenomena cause the arsenic to re-enter the water column. The arsenic cycle in aquatic systems has been investigated in the past.

2.3 HEALTH EFFECTS OF ARSENIC

The toxic effects of arsenic are well documented. Numerous accidental poisonings, in addition to many attempted and successful suicides in which arsenic is a favorite poison, are well documented in the literature. Both acute and chronic poisoning can occur. Several researchers have observed that trivalent arsenic is more toxic than pentavalent arsenic. The relative difference, however, is small, and both forms should be considered potent toxins (Maitani et al. 1987; Sardana et al. 1981; and Willhite 1981). Acute arsenic intoxication normally causes gastrointestinal symptoms within 30 minutes of ingestion. Following the gastrointestinal phase, damage to multiple organs may occur. If death does not occur within the first 24 hours due to circulatory failure, it may be caused by hepatic or renal failure over the next several days (National Research Council of Canada, 1978).

Chronic arsenic poisoning is much more insidious. Because symptoms can in many cases be nonspecific, it is not unusual for multiple hospital admissions to take place before a correct diagnosis is made. Perhaps the most notable study of arsenic arsenism has been underway in Taiwan (Tsang et al. 1968; Tsang 1977) and West Bengal, India (Das et al. 1994, 1995; Chatterjee et al. 1995). For instance, it has been reported in Taiwan that the exposed population which had an arsenic concentration of 10 μg/L to 1.82 mg/L in drinking water exhibited an increased prevalence for skin cancer that was directly correlated to the concentration and duration of arsenic intake (Tsang et al. 1968). Another study was conducted on chronic arsenic poisoning in humans in Mexico (Cebrian et al. 1994). Two targeted populations were investigated. The arsenic concentration was 7 μg/L and 410 μg/L in the control and exposed population, respectively. The prevalence of skin pigmentation changes was only 2.2 percent in the controlled population. In the exposed population, however, 21.6 percent of sample showed at least one of the cutaneous signs of chronic arsenic poisoning. Substantial evidence of carcinogenicity, mutagenicity, and/or teratogenicity has also been reported (Bencko, V. 1977).

2.4 REGULATION OF ARSENIC IN DRINKING WATER

Arsenic is regulated in drinking water. The current standard of 50 μg/L set more than 50 years ago remains in force today as the maximum contaminant level (MCL) for total arsenic. The U.S. Environmental Protection Agency (USEPA) is required by the 1986 amendments of the Safe Drinking Water Act (SDWA) to review and re-evaluate arsenic standards. Epidemiological evidence of arsenic carcinogenicity indicates that a 10^{-4} lifetime excess skin cancer risk exists as a result of exposure to arsenic in drinking water at a concentration of 2 μg/L. The range of values under consideration for a new arsenic MCL is from 2 to 20 μg/L (Pontius 1995a). In 1993 the World Health Organization (WHO) recommended a provisional guideline value of 10 μg/L based on potential health risks and a quantification limit (WHO, 1993). A recent nationwide EPA survey conducted in anticipation of proposing a revised arsenic rule indicated that 72, 22.9, 3.6, 1.4, and less than 0.5 percent of the population are exposed to arsenic levels of less than 1, 1-5, 5-10, 10-20, and above 20 μg/L, respectively, in drinking water (Reid, 1994).

2.5 ARSENIC REMOVAL TECHNOLOGIES

A number of techniques for arsenic removal from drinking waters have been studied. These are enhanced coagulation-precipitation, and reverse osmosis/membrane/ion-exchange processes, and electrotechnologies.

2.5.1 ENHANCED COAGULATION - PRECIPITATION

Many studies on arsenic removal from aqueous solutions have been conducted by using coagulation processes (Cheng et al. 1994; Gulledge and O'Connor 1973; Harper and Kingham 1992; Hering et al. 1996; McNeill and Edwards 1995; Pierce and Moore 1980, 1982; Scott et al. 1995; Shen 1973). The process may be either a conventional coagulation/flocculation process or an enhanced coagulation process. In the coagulation process, ferric chloride, ferric sulfate, and alum are the coagulants most commonly used for arsenic removal. Several studies focused on the adsorption mechanisms of arsenic on the hydrated metal oxides during the coagulation process. Softening and Fe/Mn oxidation processes are also included in this category (Edwards 1994; Harper and Kingham 1992; Pierce and Moore 1980, 1982). In the case in which arsenite was the predominant species in the water source, complete oxidation was generally required as a pretreatment step to achieve effective removal (Frank and Clifford 1986; Jekel 1994; Lauf and Wear 1993; Oscarson et al. 1983; Shen 1973; and Sinha, R. K. et al. 1993). A variety of oxidants, such as free chlorine, sodium hypochlorite, manganese oxide, potassium permanganate, hydrogen peroxide/Fe^{2+} (Fenton's reagent), ozone, and other oxidants have been used to convert As(III) to As(V).

Preliminary bench-scale and pilot-scale studies were conducted by Cheng, et al. (1994), on As(V)-spiked surface water. The results indicated that ferric chloride was much more effective than alum for As(V) removal by coagulation. The addition of polymer improved arsenic removal only when a low coagulant dose was used for both ferric chloride and alum. The initial arsenic concentration had no effect on the percent removal of arsenic. Good turbidity removal, however, was a prerequisite for effective arsenic removal. No correlation between turbidity removal and arsenic removal was established in this study.

Hering, et al. (1996), conducted comparative laboratory experiments to investigate arsenic removal by coagulation and adsorption processes. Under comparable conditions, better removal was observed for As(V) than for As(III) in both coagulation and adsorption experiments. In adsorption studies, the effects of pH on arsenic removal were not clearly shown, but a significant pH dependence was observed with a minimum removal at a pH of around 6. In the coagulation study, arsenic removal was independent of initial arsenic concentration. It was also shown that arsenic removal was a function of coagulant dosage and arsenic residual. A simplified Langmuir equation was used in that effect. Some efforts were made to simulate adsorption mechanisms by surface complexation modeling. Because of surface interactions in a real aqueous system, the modeling effort had limited success in natural waters.

An adsorption study of arsenic in an aqueous solution was performed by Pierce and Moore (1980, 1982). For both As(III) and As(V), isotherms were plotted to fit the Langmuir equation. Almost 90 percent adsorption was achieved after two hours, and one hour of stirring at pH values of 4 and 10 for both arsenite and arsenate, respectively.

Gulledge and O'Connor (1973) demonstrated by jar tests that the pH and the coagulant dosage were the main variables affecting adsorption of arsenic in conventional water treatment practices. The decreased adsorption of arsenic was observed at a pH of around 8 for both ferric sulfate and alum coagulations. Effective removal of arsenic was achieved at a lower pH range.

Based on the data collected from full-scale conventional water treatment plants, McNeill and Edwards (1995) established "profiles" of arsenic removal in different processes. Three processes studied in this work included alum coagulation, Fe-Mn oxidation, and softening. The key factors affecting arsenic removal in drinking water were identified as pH values, precipitation of $Fe(OH)_3$, and softening. In the coagulation and softening processes, As(V) removal was much lower than expected, and the soluble As(V) residual depended significantly upon formation and removal of flocculated metal hydroxide particles.

In a field study, Scott et al. (1995), reported arsenic removal rates of about 81-96 percent by ferric chloride doses of 3-10 mg/L, whereas only 23-71 percent removal by alum doses of 6-20 mg/L, respectively, occurred.

Shen (1973) presented arsenic removal data obtained in his five-year laboratory and field observations by using a combination of aeration, prechlorination, coagulation, sedimentation, and filtration processes. Ferric chloride provided the best arsenic removal from deep well water containing an initial arsenic concentration of 600 -2,000 μg/L. Aeration had no significant effect on arsenic removal, but chlorine addition during aeration improved arsenic removal by oxidation of As(III). Sinha, R. K., et al. (1993), also reported that arsenic was removed from arsenic-contaminated tubewell water by chlorine oxidation followed by coagulation-precipitation.

Natural organic matter is also effectively removed by enhanced coagulation-precipitation. Kavanaugh (1978), Semmens and Field (1980), Chadik and Amy (1983), and Sinsabaugh, et al. (1986), have shown that coagulation can be effective in removing organic compounds from natural waters. The major factors that affect removal of TOC in the coagulation process are the pH of the water, the coagulant dose and concentration, and the molecular size of the organic compounds present. Recently, Randtke (1988) summarized the major mechanisms responsible for the removal of organic compounds in coagulation as colloid destabilization, precipitation, and coprecipitation. In coprecipitation, the organic material, which is otherwise soluble, is adsorbed onto the lattice site of the growing crystals of a precipitate as an impurity. Liao and Randtke (1985 and 1986) have shown that coprecipitation is the governing mechanism for removal of fulvic acid by lime softening. Enhanced removal was observed in the presence of magnesium or phosphate ions.

Qasim, et al. (1992a), showed that low pH coagulation removed approximately 42 percent TOC at pH of around 6.3, whereas turbidity removal was approximately 96 percent. Lime softening, however, removed approximately 81 percent of the TOC at pH 10.3 with a maximum turbidity removal of 97 percent. These results clearly indicated that removal of TOC and turbidity with lime softening was superior to the low pH coagulation of the water tested.

2.5.2 REVERSE OSMOSIS/MEMBRANE/ADSORPTION/ION-EXCHANGE PROCESSES

Several studies have been conducted to investigate the feasibility of arsenic removal from drinking water by using reverse osmosis, membrane, adsorption, or ion-exchange processes (Clifford 1986; Elson et al. 1980; Ficklin 1983; Fox 1989; Fox and Sorg 1987; Hathaway and Rubel. 1987; Hering and Elimelech 1995; and Yoshida and Ueno 1978). These technologies are usually suitable for small flows treating well waters or for point-of-use (POU) treatment applications. Fox and Sorg (1987) and Fox (1989) reported the effectiveness of arsenic removal in POU treatment devices. Three processes, e.g., reverse osmosis, ion exchange, and activated alumina, were tested for arsenic removal from groundwater with natural arsenic concentrations in the range of 5-1100 μg/L. The target was set to meet the current MCL of 50 μg/L. The results showed that the low-pressure reverse-osmosis process could remove only approximately 50 percent arsenic. This removal rate was not sufficient even to meet the MCL of 50 μg/L for total arsenic when the influent arsenic concentration was higher than 100 μg/L. Another reported disadvantage of using the reverse-osmosis process was a high production of reject water (9 gallons for every gallon of finished water). High-pressure reverse-osmosis using synthetic polymeric membranes showed that the rejection of As(V) was more than 90 percent, whereas with As(III), it is less than 70 percent (Fox 1989; Fox and Sorg 1987). Water pH is extremely important for arsenic rejection as arsenic species in water are highly pH-dependent. In a recent study, Hering and Elimelech (1995) reported that RO and "tight" nano-filtration membranes effectively removed arsenic from natural water that was spiked with high arsenic. Similar removal for both As(III) and As(V) was observed, and the performance of membranes was also comparable regardless of the presence of turbidity-causing materials, dissolved organic matter, and inorganic components.

Arsenic adsorption onto various adsorbents has been studied. Among these are aluminum oxide, iron oxide, activated carbon, and multifunctional chemisorption filters that combine the effects of adsorption, ion exchange, and filtration (Rajaleovic and Mitrnovic 1992). Fluoride and As(V) are strongly adsorbed/exchanged by activated alumina. The arsenic removal system using an activated alumina column has been investigated extensively for small communities using groundwater (Bellech 1971; Rubel and Williams 1980; and Hathaway and Rubel 1987). Activated alumina has an equilibrium capacity of As(V) up to 10 times that of As(III).

Ion exchange with strong base resins has been used for arsenic removal from groundwater supplies. Divalent As(V) ($HAsO_4^{2-}$) appears to be the preferred species over monovalent ion. Hathaway and Rubel (1987), in their pilot plant investigation, found that strong-base anion exchange resin was inefficient for removal of As(V) because of the competition with the high sulfate concentration in water.

Ficklin (1983) also studied arsenic removal by anion exchange. He found that As(V) could be removed effectively in a column, but As(III) had a poor removal rate. In another investigation, conducted by Yoshida and Ueno (1978), As(V) and As(III) had almost identical removal rates. The optimum pH range for As(V) was 3-6, and that for As(III) was 8-9.

2.5.3 THE EMERGENCE OF ELECTROTECHNOLOGIES

A number of electrotechnology-based treatment systems are gaining acceptance in water treatment. These technologies are used for disinfection; taste and odor control; destruction of undesired organic contaminants, including chlorinated hydrocarbons; removal of metals by electrode position; electrochemical precipitation; and electrochemical-based analytical procedures for arsenic determination. Ozonation of water is an emerging electrotechnology in the United States. Ozone, a strong oxidizing agent, produced by passing an electric current through oxygen, gas, or dried air, is increasingly used in water treatment for disinfection and other treatment. As a disinfectant, using a CT measure, ozone is 100 to 300 times as effective as chlorine in killing *Giardia lamblia* cysts. In addition to disinfection, ozonation has other attractive advantage of forming significantly reduced levels of trihalomethanes (THMs) and haloacetic acids (HAAs) (Anonymous 1993b; Douglas 1993; Najm and Krasner 1995).

Recent studies have shown that ozonation of raw water changes particle behavior. In particular, the floc becomes larger and TOC and turbidity removal is enhanced. This improves floc settling properties, extends filter runs, or delays turbidity breakthrough. As a result, plant performance is improved even at a decreased coagulant chemical dosage. Edwards and Benjamin (1991), Grasso and Weber (1988), and Chang and Singer (1991) have reported the mechanics of ozone-induced particle destabilization. Reckhow and Singer (1984) studied removal of organic halide precursors by preozonation and alum coagulation. Cromley and O'Connor (1976) reported the effect of ozonation on the removal of iron from groundwater. Saunier, Selleck, and Trussell (1983) studied preozonation as a coagulant aid in drinking water treatment. The City of Fort Worth funded pilot plant studies in conjunction with the design of Eagle Mountain Water Treatment Plant and was able to significantly decrease sedimentation times and increase filter-loading rates for the new plant as a result of selecting ozonation as the principal disinfectant.

Ultraviolet (UV) light, another electrotechnology, has shown high inactivation of the enteric virus, but poor inactivation of *Giardia lamblia* cysts. Lack of effectiveness in killing cysts and the inability to have residual have limited use of this technology in drinking water disinfection. A recently developed CAV-OX® ultraviolet oxidation process destroys organic contaminants, including chlorinated hydrocarbon in water (U.S. EPA 1993). EPRI has also sponsored a project with electron-beam disinfection that involves bombarding the water with high-energy electrons from a particle accelerator. The fast-moving electrons and the chemical radicals created by their impact destroy both microorganisms and organic contaminants (Douglas 1993).

Agarwal et al. (1984), reported electrode position of six heavy metals on the Reticulated Vitreous Carbon (RVC) electrode. The removal achieved was up to 100 percent from water containing very low concentrations of metals. Andco Environmental Processes, Inc. (Anonymous, 1993a), is marketing an Andco electrochemical system that removes heavy metals from groundwater, surface water, or leachate. DC current across a carbon steel electrode generates an insoluble iron matrix which adsorbs and coprecipitates heavy metals and other contaminants from the water. The insoluble constituents are then separated from the aqueous stream by clarification.

The Department of Chemistry at The University of Texas at Arlington (UTA) has utilized photocatalytic reduction and immobilization of hexavalent chromium at titanium dioxide in aqueous-basic media (Lin et al. 1993). The technique seems applicable to removal of arsenic from drinking water.

Chapter 3
OCCURRENCE OF ARSENIC IN SURFACE WATER SOURCES IN TEXAS

3.1 DATA SOURCES

The State of Texas Water Quality Inventory is prepared by the TNRCC, and submitted to the EPA biennially in even-numbered years in accordance with Section 305(b) of the Clean Water Act. This report enables the public, local governments, state agencies, the Texas Legislature, EPA, and the U.S. Congress to evaluate water quality in Texas.

The TNRCC maintains an ambitious surface water quality monitoring (SWQM) program in order to characterize existing water quality and emerging problems, define long-term trends, determine water quality standards compliance, and describe the seasonal variation and frequency of occurrence of selected water quality constituents. Approximately 700 fixed SWQM sites are sampled by the TNRCC with the frequency of sampling and parametric coverage dependent on specific needs and location. A long list of organic substances and heavy metals is monitored in water, sediments, and fish tissue. Total arsenic is one of the items on the list.

The TNRCC supplied the arsenic data via the Internet by way of their BBS. The data files contained sampling information from all of the sampling points. The data was in latitude-longitude, data and location of samples, and arsenic concentrations in $\mu g/L$.

3.2 COORDINATE CONVERSION AND PLOTTING OF CONCENTRATIONS

The conversion of different coordinate systems and preparation of an arsenic concentration profile map were conducted by Chiang, Patel and Yerby, Inc., in accordance with the following procedures:

- Several computer software programs were utilized, ranging from modem software to CADD software, to reduce the data files to latitude-longitude coordinates and arsenic concentrations.
- The data file was then run through Corpscon, a data conversion software, to convert the latitude-longitude coordinates to the Texas State Plane Coordinate System.
- Then the data file was run through Lotus 123 to average each one of the sampling points to just one coordinate and one value per sampling point.
- The data file was imported into Microstation program using Geopak, a civil engineering design software, and the data points were then contoured to illustrate the levels of occurrence of arsenic.
- The CADD file was finally plotted on a Hewlett Packard 1200C color printer.

3.3 CONCENTRATION PROFILE

The profile of arsenic concentration in the surface water sources in Texas is shown in Figure 3-1. The levels of occurrence of arsenic in different ranges are indicated by various color bands. It may be clearly noted that a major portion of Texas has arsenic concentration below 5 μg/L, followed by 5 - 10 and 11 - 20 ranges. Several areas in Texas have arsenic concentrations in the ranges of 21 - 30, 31 - 40, and above 40 μg/L.

There are approximately five areas of high arsenic where the concentration in natural waters exceed 30 μg/L. These areas are near Bryan-College Station, Austin, Houston and the Houston ship channel, Galveston, and coastal areas around Harlingen. In addition, there are some small areas where the concentration exceeds 30 μg/L.

The sources of arsenic from manmade activity may originate from a variety of industrial processes. Arsenic-containing compounds are also commonly used for agricultural applications which may account for 75% of the total commercial consumption. The common industrial sources of arsenic are metallurgical industries, semiconductor manufacturers, solar cell manufacturers, electrophotography, battery plates, glass industry, pharmacies, and munition industries. The

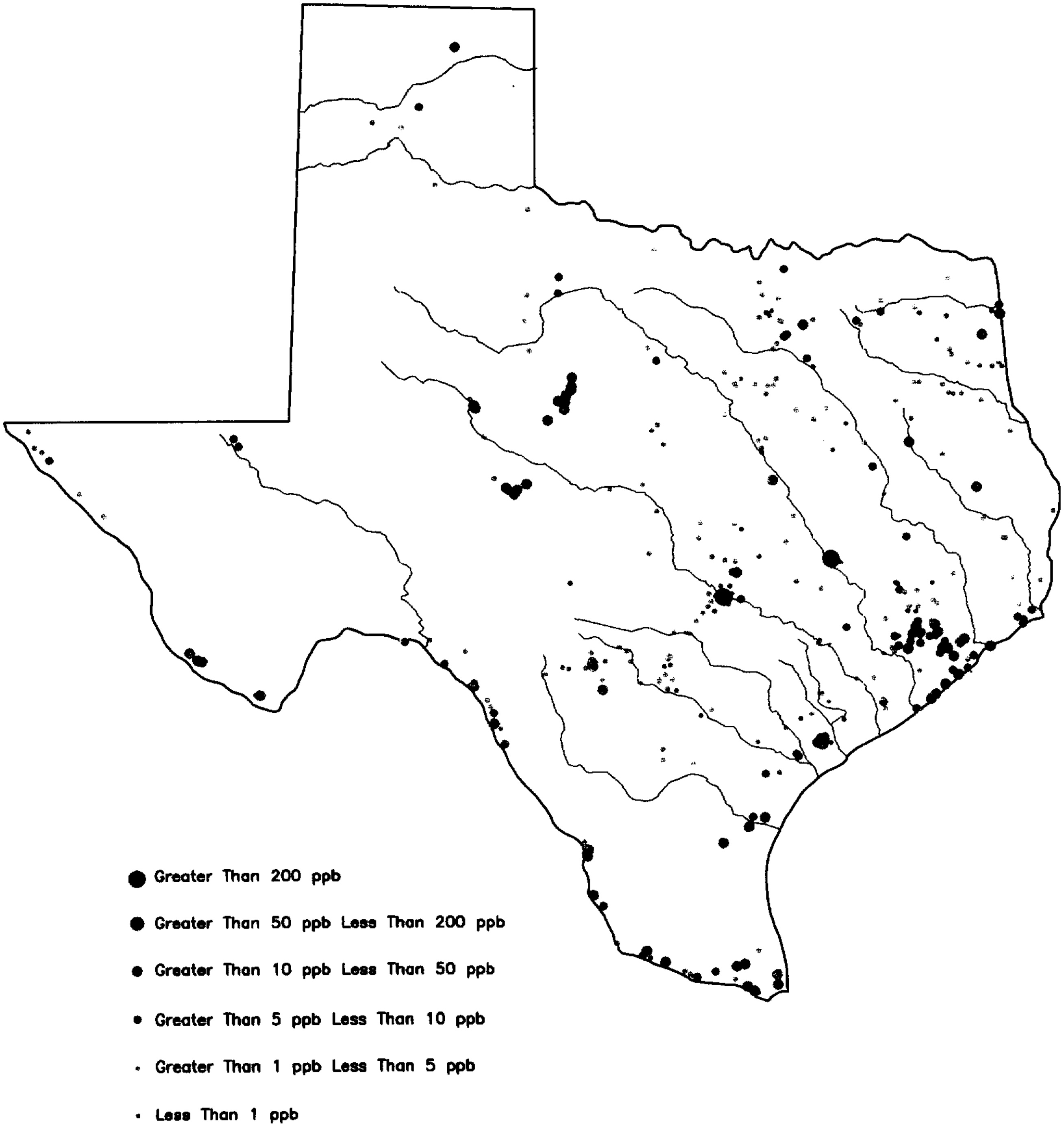

FIGURE 3–1

Preliminary Arsenic Profile Map for the State of Texas common agricultural sources are the manufacture and application of pesticides, insecticides, herbicides, silvicides, defoliation of cotton, wood preservatives, poultry feed additives, and disease treatment in livestock. It is suspected that arsenic in bodies of water may come from industrial activity runoff and the application of agricultural chemicals.

The arsenic source identification in Texas is not the scope of this investigation. As part of this study, the arsenic profile in natural waters of Texas has been developed. In-depth studies are needed to develop a relationship between the high levels and sources of arsenic in Texas water systems.

Chapter 4

ENHANCED COAGULATION STUDIES USING JAR TEST APPARATUS

A number of bench-scale coagulation studies were conducted using jar test apparatus. These studies were aimed at establishing coagulation diagrams, assessing the effect of preozonation on arsenic removal, estimating sludge production, and investigating arsenic removal mechanisms.

Coagulation diagrams are useful tools for predicting and defining the chemical conditions under which coagulation occurs. The preozonation experiments provided information about the oxidation of arsenic species [As(III) to As(V)] and its enhanced removal. Sludge production generally increases with coagulant dosage, and therefore sludge quantities must be determined to develop final disposal options for the residuals. Finally, the purpose of the experiments on arsenic removal mechanisms was to determine arsenic removal efficiencies and to identify those factors that may influence arsenic removal by the coagulation process.

The standard jar test apparatus was used exclusively in these investigations. The materials and methods utilized are presented below.

4.1 JAR TEST PROTOCOL

The experimental protocol included the following major items: (a) water samples, (b) chemicals, (c) a jar test procedure, (d) coagulant doses, (e) pH adjustment, and (f) analytical work. Each of these items is briefly described below.

4.1.1 WATER SAMPLES

The raw water test samples were collected from the raw water line in the pilot plant building at the Rolling Hills Water Treatment Plant (RHWTP). The water samples were stored in a clean 50-

gallon Nalgene container. A well-mixed sample was analyzed for background levels. The raw water was then spiked with a standard arsenic solution to give the desired arsenic concentration.

To make artificial water samples, the water samples were collected from a tap water hose at the pilot plant at the RHWTP. The tap water was also spiked with a standard arsenic solution to give the desired arsenic concentration. The artificial turbidity for the arsenic removal mechanism experiment was induced by spiking tap water with a standard kaolin solution. Information on the relationship between the turbidity produced and the kaolin dosage applied is provided in Appendix D.

4.1.2 COAGULANTS

Primary coagulants utilized during this program included ferric sulfate, ferric chloride, and alum. All coagulants were industrial-grade-quality chemicals obtained from the water treatment plants. Sulfuric acid, sodium hydroxide, and quick lime were used for pH adjustment. Analytical-grade arsenic compounds were used for arsenic spiking. Ozone was generated onsite for preozonation of raw water. Artificial turbidity was induced by adding analytical-grade kaolin in tap water. The available information on chemicals used is summarized in Table 4-1.

4.1.3 JAR TEST PROCEDURE

The standard Phipps and Bird jar test apparatus with variable-speed drive, and six two-liter square jars, was used. High-speed mixing and three-stage flocculation at different G values was followed by simulating the rapid mixing, tapered flocculation, and gravity settling of a conventional water treatment plant. The rapid mixing was simulated at a velocity gradient of 95 per sec for 30 sec. The tapered flocculation was simulated as follows:

> The *G* values and detention times for Stages I, II, and III were, respectively, 60 per sec, 7.5 min; 30 per sec, 7.5 min; and 15 per sec, 10 min. The settling detention time was one hour.

TABLE 4-1
CHEMICALS USED IN JAR TEST STUDIES

CHEMICALS	CHEMICAL FORMULA	GRADE	MANUFACTURER	OTHER DESCRIPTIONS
Primary coagulant				
• Ferric sulfate liquid	$Fe_2(SO_4)_3$	Commercial	Fe-3, Inc.	$Fe_2(SO_4)_3$ = 38 % w/w Fe(III) = 10.5 % w/w
• Ferric chloride liquid	$FeCl_3$	Commercial	Midland Resources Inc.	$FeCl_3$ = 41 % w/w Fe(III) = 14.0 % w/w
• Alum solution liquid	$Al_2(SO_4)_3$	Commercial	Stauffer	Al_2O_3 = 8 % w/w Al(III) = 4.2-4.5 % w/w
pH adjustment				
• Sulfuric acid solution	H_2SO_4	Reagent	Fisher Scientific	
• Sodium hydroxide solution	NaOH	Reagent	Fisher Scientific	
• Quick lime solid	$Ca(OH)_2$	Commercial	Texas Lime Co.	CaO Content: 70-90 % w/w
Arsenic spiking chemicals				
• Arsenic trioxide	As_2O_3	Reagent	Sigma Chemical Co.	
• Sodium arsenate	$Na_2HAsO_4 \cdot 7H2O$	Reagent	Sigma Chemical Co.	
Ozonation agent				
• Ozone generator using O_2 for feed	O_3	—	Griffin Technics Inc. (for ozone generator)	Ozone content in O_2 gas: 1 - 2 % w/w
Artificial turbidity spiking material				
• Kaolin	$H_2Al_2Si_2O_8 \cdot H_2O$	U.S.P. grade	Fisher Scientific	

4.1.4 COAGULANT DOSAGE

The dosage of all primary coagulants in each jar was controlled on the basis of the liquid feed. The minimum and maximum dosages used in this study were 20 to 120 mg/L for iron-based coagulants. For alum, the dosages were in the range of 40 to 240 mg/L.

The liquid dosages of all coagulants were then converted to metal ion concentrations. The trivalent metal ion contents in the coagulants ferric sulfate, ferric chloride, and alum were 10.5, 14.0, and 4.2 percent by weight, respectively.

4.1.5 pH ADJUSTMENT

The pH of raw water was adjusted by adding acid or base before starting the coagulation process. The final pH of settled water was the target. Acid and base titration curves were developed for each coagulant at different doses. The acid and base quantities were obtained from these curves for pH adjustment in the jar tests. These acid-based titration curves are provided in Appendix C.

4.1.6 ANALYTICAL WORK

Many chemical tests were conducted on raw and coagulated water samples for each jar test. Temperature, pH, turbidity, particle count, total suspended solids (TSS), total alkalinity, and total hardness measurements were made at the pilot plant or at the water quality laboratory of Department of Civil and Environmental Engineering at UTA. Inchcape Testing Services in Richardson, Texas, was retained to conduct total and dissolved arsenic and TOC and DOC measurements. The RHWTP coordinated the sample delivery and data acquisition. Also, the water quality laboratory at the RHWTP performed UV254 and total THM measurements. In addition, the raw water quality data developed by the RHWTP for concerned dates were used in this study. All analytical procedures utilized in this study were EPA-approved and/or were standard procedures given in the standard methods.

4.2 EXPERIMENTAL DESIGN

A number of jar tests were designed to develop data on coagulation diagrams, preozonation, sludge production, and arsenic removal mechanisms. The experimental design is presented in this section.

4.2.1 RAW WATER SAMPLING

Five batches of raw water samples and one tap water sample were collected and stored for various jar tests. The dates of the sample, as well as water blend information on Cedar Creek and Richland-Chambers Reservoirs, as reported by TCWCID No. 1, are summarized in Table 4-2. The background level of arsenic in surface water source at RHWTP was low (2 to 4 μg/L). At such a low background level, the performance of treatment processes was difficult to evaluate. Therefore, the raw water samples for developing the coagulation diagram and arsenic removal mechanism were spiked with arsenic salt, [As(V)], and stored in the container for the jar tests. The water sample collected and stored in the container for the sludge production experiment was not spiked with arsenic. The water samples for preozonation experiments were *freshly* spiked with either arsenic trioxide [As(III)] or arsenic salt [As(V)]. No storage was necessary for preozonation experiments. Detailed water quality data may be found in Appendix B.

TABLE 4-2
WATER SAMPLE COLLECTION INFORMATION

SPIKED WATER SAMPLE BATCH CODE	COLLECTION DATE	BLENDING RATIO[1]	ARSENIC SPIKING AND STORAGE	EXPERIMENTAL PURPOSE
SWS-1	May 22, 1995	33:67	A(V) spiking and storage	Coagulation diagram
SWS-2	July 13, 1995	22:78	AS(V) spiking and storage	Coagulation diagram
SWS-3	September 26, 1995	22:78	Storage w/o As spiking	Sludge production
SWS-4	November 9, 1995	0:100	As(III) freshly spiking; no storage	Preozonation
SWS-5[2]	January 29, 1996	34:66	As(V) spiking and storage	Arsenic removal mechanism
SWS-6[3]	April 25 - May 10, 1996	37:63	As(III) freshly spiking; no storage	Preozonation

[1] Blending ratio is expressed as flow rate from Cedar Creek Reservoir: flow rate from Richland Chambers Reservoir.

[2] The tap water produced by the RHWTP was utilized as a water sample, with artificial turbidity by kaolin-spiking. The blending ratio was that of the raw water influent to the RHWTP.

[3] A freshly spiked water sample was drawn from the ozone contact chamber at the pilot plant of the RHWTP before conducting the jar tests. The blending ratio was the average during the test period.

4.2.2 JAR TEST PLANNING AND OPERATIONAL CONDITIONS

Fifty-six jar tests were conducted during this program. Out of these, 11 jar tests were performed to test and calibrate the equipment, procedure and analytical techniques, and to develop preliminary information on the overall project objectives. Included in these jar tests are runs that failed to provide the target condition of the experimental design. Therefore, not all the data for 11 jar tests have been included in this report; only 45 jar test data sets have been used to develop the information and meet the research objectives. Jar test experimental conditions are presented in Table 4-3. Specific operational conditions for each jar test are provided in Appendix A.

TABLE 4-3
SUMMARY OF JAR TEST EXPERIMENTAL CONDITIONS

EXPERIMENTAL PURPOSE	NUMBER OF JAR TESTS	CHEMICAL CONDITIONING							
		w/ferric sulfate	w/ferric chloride	w/alum	w/pH adjustment	w/As(V)	w/As(III)	w/ozone	w/kaolin
Coagulation diagram	21	12	7	2	16	21			
Preozonation	7	2	5			1 (w/O_3)	6(3 w/O_3)	4	
Sludge production	6	2	4		6				
Arsenic mechanism removal	11		11		3	11			6
Total	45	16	27	2	25	33	6	4	6

NOTE: (1) Number of jar tests without pH adjustment = 45-25 = 20.
(2) Number of jar tests without arsenic spiking = 45-(33+6) = 6.

The entire experimental program for jar testing was designed to develop information on the following major target areas:

- Coagulation diagrams
- Preozonation
- Sludge production
- Arsenic removal mechanisms

A brief discussion of each of these target areas is given below.

Coagulation Diagrams

The experiments for developing coagulation diagrams were conducted with different coagulants. Three commonly used coagulants utilized in the jar tests were ferric sulfate, ferric chloride, and alum. The jar tests conducted with ferric sulfate, ferric chloride, and alum were 12, 7, and 2, respectively. For each coagulant, the operational variables were pH and coagulant dosage. Sixteen jar tests were conducted with pH adjustment by adding sulfuric acid, sodium hydroxide, or lime. The coagulant dosages investigated covered the typical range normally used in conventional water treatment practices, as well as those used in many research studies for enhanced coagulation process. As(V) was the only species investigated for this purpose. Initial total arsenic concentrations after spiking were in the range of 10 - 20 μg/L.

The targeted final pH range of settled water for all jar tests conducted with iron-based coagulants was between 5 and 10. The dosages ranged between 20 and 120 mg/L as liquid. This range corresponded with the Fe(III) concentrations from 2.1 to 12.6 mg/L for ferric sulfate, and from 2.8 to 16.8 mg/L for ferric chloride.

For alum coagulation, only two pH levels were targeted. These levels were pH 5 and ambient pH. The liquid dosage was in the range of 40 to 240 mg/L. This gave Al(III) concentrations of between 1.7 to 10.1 mg/L.

Preozonation

The purposes of the preozonation experiment were (a) to compare removal of As(III) with that of As(V), and (b) to determine the effect of preozonation upon the removal of As(III). Therefore, both As(III) and As(V) spiked water samples were utilized in the jar tests. The types of coagulants and their dosages were also operational variables. The pH adjustment, however, was not considered in the preozonation experiments.

Ozonation is generally characterized as an oxidation process. The oxidation of arsenic may occur as ozone reacts with lower-state arsenic species. As a result, As(III) is likely to be converted into As(V) species. Since the removal of arsenic species in one oxidation state may differ significantly from that in the other oxidation state, the mechanism of arsenic removal by coagulation may also change when preozonation is utilized. Seven jar tests were conducted with and without preozonation using As(III) and As(V) species. Table 4-4 provides a summary of the jar test matrix and initial total arsenic concentrations in the spiked water.

TABLE 4-4
JAR TEST MATRIX UTILIZED
IN PREOZONATION EXPERIMENTS

Arsenic Species	Number of Jar Tests with Ozonation	Number of Jar Tests Without Ozonation	Initial Total Arsenic Concentration μg/L
As(III)	3	3	10 - 30
As(V)	1	0	10

The preozonation procedure for the jar tests was as follows: freshly spiked raw water samples were ozonated in the ozone contact chamber of the pilot plant at the RHWTP. The ozonated water samples were then drawn from the ozone contact chamber for the jar tests. A typical jar test procedure was used for both ozonated and nonozonated water samples. Both ferric sulfate and ferric chloride were used in the study. Five jar tests were conducted with ferric chloride at Fe(III) dosages ranging from 2.8 to 16.8 mg/L. In the other two jar tests, ferric sulfate was utilized and the Fe(III) dosages were between 2.1 and 12.6 mg/L.

Sludge Production

A number of jar test experiments were conducted for estimating sludge production rate. The experimental variables were the same as those for preparation of the coagulation diagram. Two iron-based coagulants, ferric sulfate and ferric chloride, were applied at Fe(III) dosages of 2.8, 5.6, 11.2, and 16.8 mg/L. The sludge production rates were studied under natural and acidic conditions. At each coagulant dose, two and four pH levels were selected for ferric sulfate and ferric chloride, respectively. The pH adjustment was made by adding sulfuric acid.

The sludge quantity data were obtained by performing the standard TSS analysis on coagulated water samples. The sludge volume was measured by using the standard 1-liter Imhoff cone apparatus following a typical jar test procedure. No arsenic spiking was applied. Arsenic concentrations in the sludge were estimated from the predictions of both the amount of arsenic removed and the amount of sludge produced by the coagulation process.

Arsenic Removal Mechanism

The experiments on arsenic removal mechanisms were designed to study the arsenic removal rate and identify those factors that may influence the coagulation process. In this investigation, As(V) and Fe(III) were the only arsenic source and metal ion for coagulation, respectively. The jar tests were conducted at different initial arsenic concentrations, initial turbidity levels, coagulant dosages, and pH conditions. The ferric chloride dosages in all jar test experiments were in the range of 2.8 - 16.8 mg/L as Fe(III).

Natural turbidity interferes with both steps; therefore, in these investigations, tap water was exclusively used, with known turbidity artificially induced. The benefit of using tap water is that it generally retains the essential chemical components of the surface water and is almost turbidity-free. The tap water was spiked by a kaolin solution when an initial turbidity was desired. The tap water was collected and stored in two containers. The water in one container was spiked with a standard arsenic solution to give a total arsenic concentration of approximately 100 μg/L. Eleven jar tests were conducted in this experiment. The operational conditions are given below.

Four jar tests were conducted with turbidity-free water samples at four initial arsenic concentrations of 100, 50, 25, and 12.5 μg/L. The lower concentrations were made by diluting the 100 μg/L arsenic-spiked sample with tap water stored in the second container.

The effect of turbidity on arsenic removal was studied by using artificial turbidity. Kaolin is a standard clay material made of hydrated aluminum silicate. Kaolin causes turbidity when it is added to water. It is one of the most common spiking agents used to simulate inorganic colloidal particles in natural water. Four additional jar tests were conducted by using the water samples spiked with kaolin: three with an initial total arsenic concentrations of 100 μg/L and initial turbidity levels of 10, 20 and 40 NTU. The remaining jar test was conducted at an initial total arsenic concentration of 50 μg/L and an initial turbidity level of 40 NTU. No pH adjustment was made in these jar tests.

The last three jar tests were conducted under acidic conditions by adding sulfuric acid. The final pH in settled water of all of these jar tests was approximately 6. Two water samples in this group were tested with an initial total arsenic concentration of 50 μg/L. One sample was free of turbidity, and the other had an artificial turbidity of 40 NTU. The third jar test was conducted at an initial total arsenic concentration of 100 μg/L and an initial artificial turbidity level of 20 NTU.

4.3 RESULTS AND DISCUSSION

The generalized results of the experiments on jar testing are summarized and discussed in this section. The discussion is presented in four major areas: coagulation diagrams, preozonation, sludge production, and arsenic removal mechanisms. Original experimental data are provided in Appendix B.

4.3.1 COAGULATION DIAGRAMS

The coagulation diagram provides a graphic representation of the removal of a targeted constituent as a function of pH value and coagulant dosage. In this study, the targeted constituents are (1) turbidity, (2) arsenic, (3) organic carbon, and (4) absorbance at UV254 nm.

Turbidity is traditionally the primary target that must be removed from the raw water source in a conventional water treatment plant. Turbidity is generally caused by colloidal particles in the water. These small particles may originally be present in a raw water source or formed by precipitation of metal coagulants during the coagulation process. Turbidity removal is closely dependent upon (1) removal of naturally occurring inorganic and organic particulate materials, such as clays, algae, bacteria, viruses, and color- and odor-producing matters, in raw water and (2) removal of floc formed of amorphous metal hydroxides on which many contaminants, such as heavy metals, arsenic species, and NOM, may be attracted. The turbidity removal, therefore, is the most important parameter required to evaluate coagulation conditions and treated water quality. The coagulation diagram for turbidity removal thus provides a foundation on which the kinetics and removal mechanisms governing the coagulation process can be explained.

Coagulation diagrams for other contaminants are also valuable tools for determining optimum operational conditions for removal of contaminants. Arsenic removal is the major thrust of this study. The coagulation diagram for arsenic removal provides the process efficiency for arsenic removal and a visual indication of the best and worst operational conditions regarding pH and coagulant dose.

Coagulation diagrams for removal of organic compounds are also an important consideration in meeting the conditions required by the disinfection by-product rules. The removal of NOM [especially the dissolved organic matter (DOM)] by the coagulation process is highly dependent upon its characteristics, charge, and solubility. These characteristics are pH-dependent and are affected by the addition of a metal-salt coagulant. Water samples for jar tests were sent for both TOC and DOC analyses. Because of data inconsistency and reversal that occurred with TOC and DOC analyses, the coagulation diagram for DOC removal could not be completed. However, the coagulation diagram for UV254 absorbance was prepared. Because of the suggested close relationship between DOC concentration and UV254 absorbance, these diagrams may give an indication of DOM removal by the coagulation process.

Coagulation diagrams were prepared for percent removal of the desired constituents. For each constituent, the experimental results were plotted first on a grid, with the X- and Y-axes being pH and coagulant dosage, respectively. All these plotted grids are provided in the appendices. Based on these original plots, the iso-removal contours are then drawn to prepare the coagulation diagrams. The iso-removal curves obtained by using all actual data points may not be a true representation of the removal trend because a few erroneous data points may distort the entire shape of the coagulation diagram. Therefore, the iso-removal contours are drawn within the grid by visual best-fit lines. The coagulation diagrams thus developed are greatly simplified and are presented in this section. Readers should refer to Appendix E for in-depth coverage of this topic.

Coagulation diagrams for both ferric sulfate and ferric chloride have been completed. The data on alum coagulation are not sufficient to warrant preparation of coagulation diagrams for any constituent studied.

FERRIC SULFATE COAGULATION DIAGRAMS

For ferric sulfate coagulation, 12 jar tests were conducted at different coagulant dosages and pH conditions. Summary information about these jar tests and the experimental data are provided, respectively, in Appendices A and B. The experimental region covered in the coagulation diagram is the area within pH values from 4.2 to 9.3, and with coagulant dosages from 2.1 to 12.6 mg/L as Fe(III). Figure 4-1 shows a sample grid of all experimental conditions that were covered in the

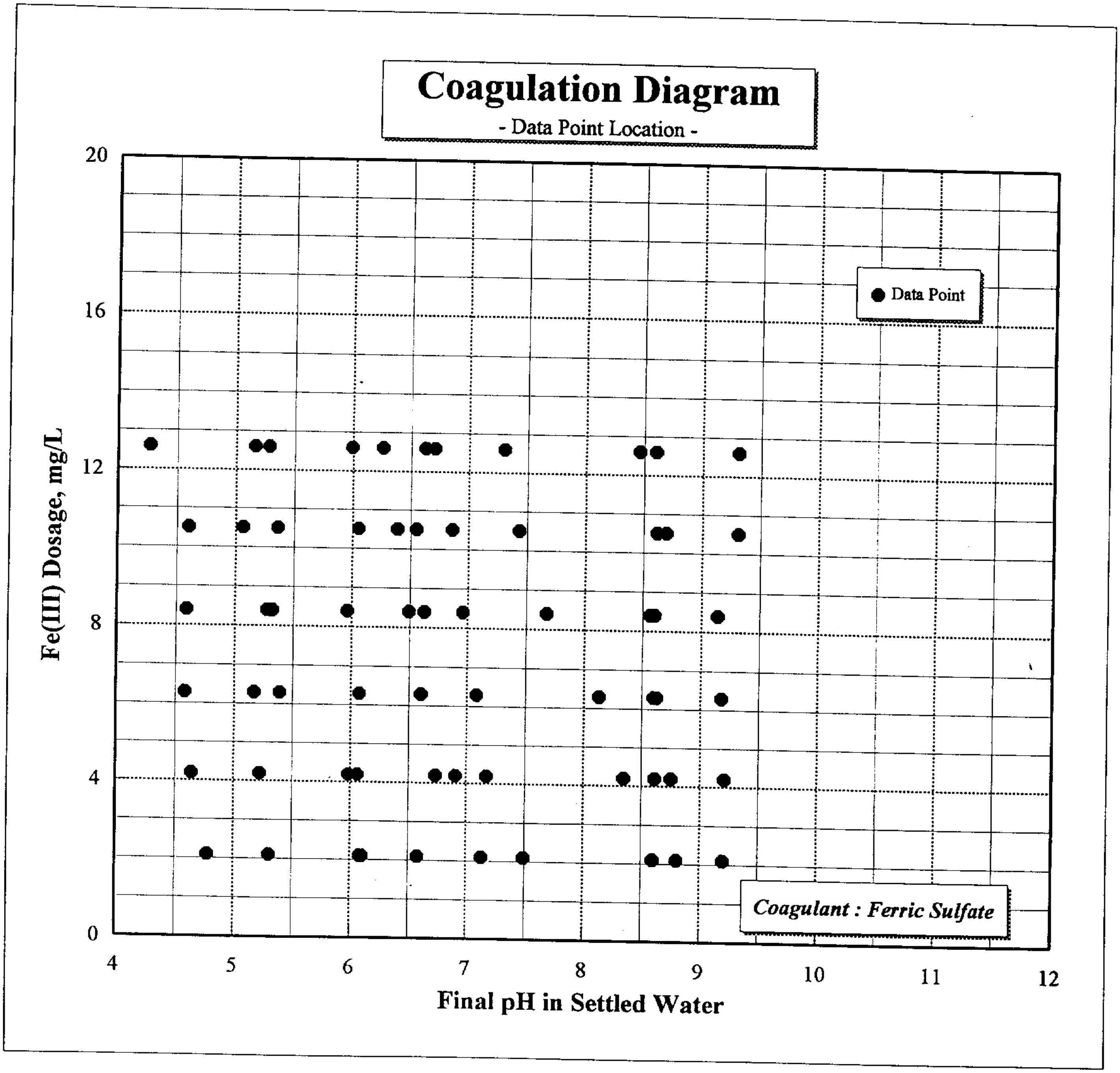

FIGURE 4-1

Sample Data Point Locations for Preparation of Coagulation Diagrams with Ferric Sulfate jar test for each constituent. Based on the removal data obtained under these conditions, the coagulation diagrams were prepared for each targeted constituent.

Turbidity Removal

The simplified coagulation diagram showing turbidity removal at different pH values and ferric sulfate dosages is shown in Figure 4-2. A significant pH dependence was observed at all coagulant dosages used in the jar tests. Effective turbidity removal (>80 percent) was reached at a pH of about 4.5 - 5, and 8.5 when a Fe(III) dosage higher than 6 - 8 mg/L was applied. The best turbidity removal (>95 percent) was achieved at a pH of about 5 and Fe(III) dosages of 10 - 12 mg/L. The worst pH range for turbidity removal was 6 - 7, at which very poor turbidity removal (<50 percent) was observed. Within this range, no significant improvement was found, even though a coagulant dosage of up to 8 - 10 mg/L as Fe(III) was added. A decreased removal of turbidity was observed under partial softening conditions (pH around 9.5) with total hardness removal of 10 - 30 percent by adding lime.

It is interesting to note that the worst pH range is located close to the lower pH boundary of the sweep-coagulation zone reported in the literature (Johnson and Amirtharajah 1983). The poor turbidity removal may be caused by the transition of predominated coagulation mechanisms from a sweep-coagulation mode to an adsorption-destabilization mode. The possible reason for the transition between the mechanisms may be the smaller size of the amorphous ferric hydroxide precipitates newly formed in this pH range as compared to those formed under pH conditions for sweep-coagulation. Since the size of the newly formed amorphous ferric hydroxide precipitates is smaller, the total surface area of these small particles then becomes larger. The dependence of coagulation efficiency upon the colloidal surface area in the adsorption-destabilization mode has been confirmed by Rubin and Kovac (1975). Therefore, a high coagulant dosage (as an electrolyte) is stoichiometrically required in order to provide enough concentration of counter-ions for adsorption and charge neutralization. At a low coagulant dosage, most newly formed ferric hydroxide particles did not settle because of poor destabilization of colloids. The colloidal suspension that did not settle had a yellow color. The presence of yellow color induced by unsettled ferric hydroxide, along with high turbidity remaining after sedimentation, is evidently consistent with this statement.

At pH values lower than the worst pH conditions, improved turbidity removal may be due to charge reverses that occur on the edge of some plate-like particles. For instance, it has been suggested by Alince and van der Ven (1993) that the zero point of charge (z.p.c.) on the edge of clay particles is generally in the pH range of 5.8 to 7.3. By lowering the pH below the z.p.c., the electrostatic interactions between the positive-charged edge and the negative-charged surface can lead to an edge-face attraction. As a result, an open card-house structure can be formed. This type of structure has a relatively high capability to trap other impurities into its frame. A great number of small colloidal particles, including the newly formed amorphous ferric hydroxide precipitates, can be effectively removed in this way.

At pH values higher than the worst pH conditions, sweep-coagulation, of course, is the predominant mechanism for enhancing turbidity removal. Improved removal of turbidity in a pH range between 7.5 and 9 may be due to this reason.

When the pH values are high enough to allow the softening process to occur, the removal of turbidity can be impacted by the increased solids loading due to the formation of crystal calcium carbonate and amorphous magnesium hydroxide precipitates. In the partial softening process, however, only calcium carbonate precipitates are usually produced. These fine crystals have a very poor settling property (Amirtharajah and O'Melia 1990). Therefore, the observation of increased turbidity at a high pH may be due to the high calcium carbonate crystals concentration remaining in the settled water.

Arsenic Removal

The coagulation diagram for total arsenic removal in settled water is shown in Figure 4-3. The effect of pH on arsenic removal is very similar to effect on turbidity removal. Higher than 80 percent of the initial total arsenic can be effectively removed after settling at a pH of about 4.5 and

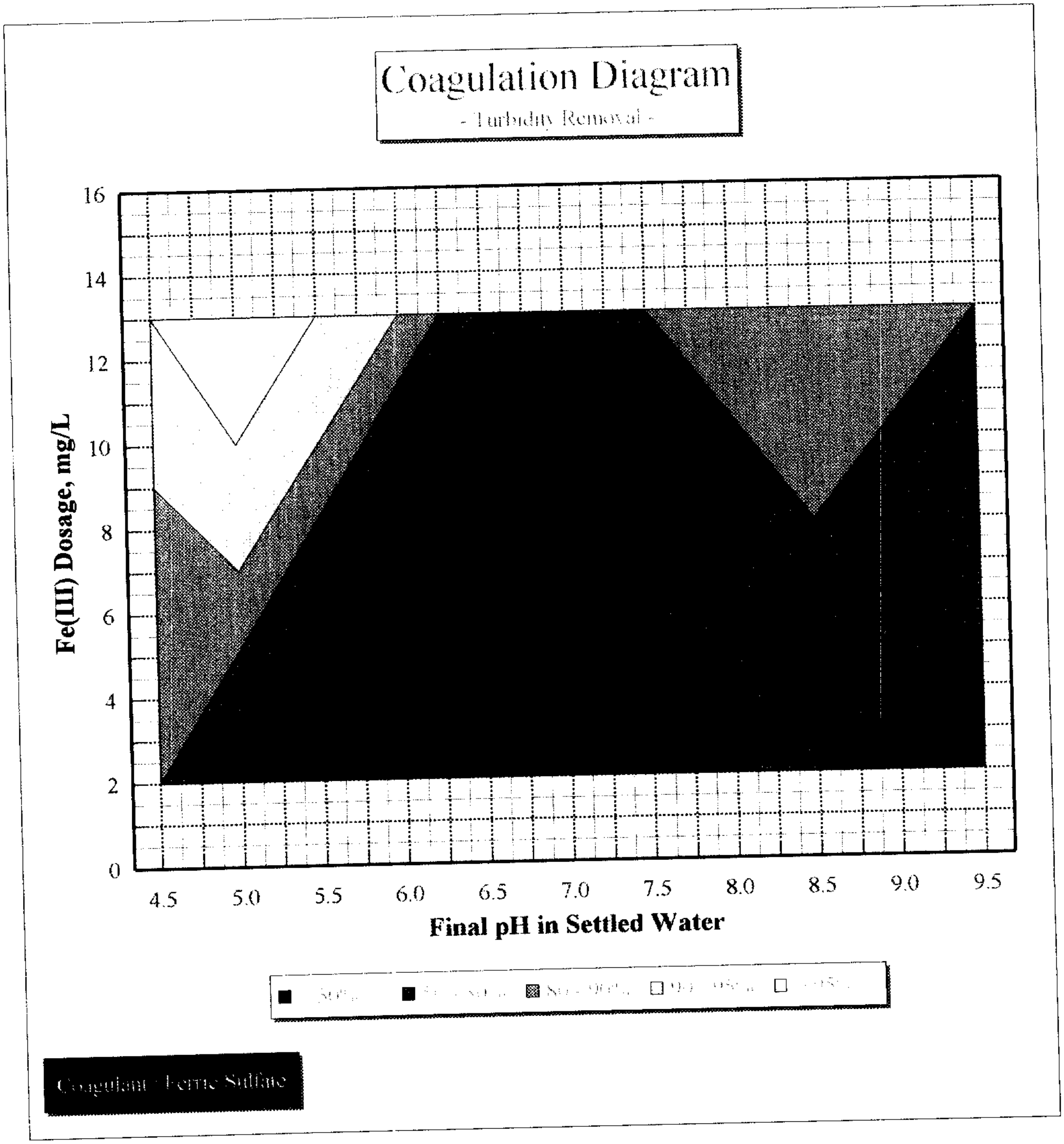

FIGURE 4-2
Coagulation Diagram for Turbidity Removal in Settled Water
with Ferric Sulfate Coagulation

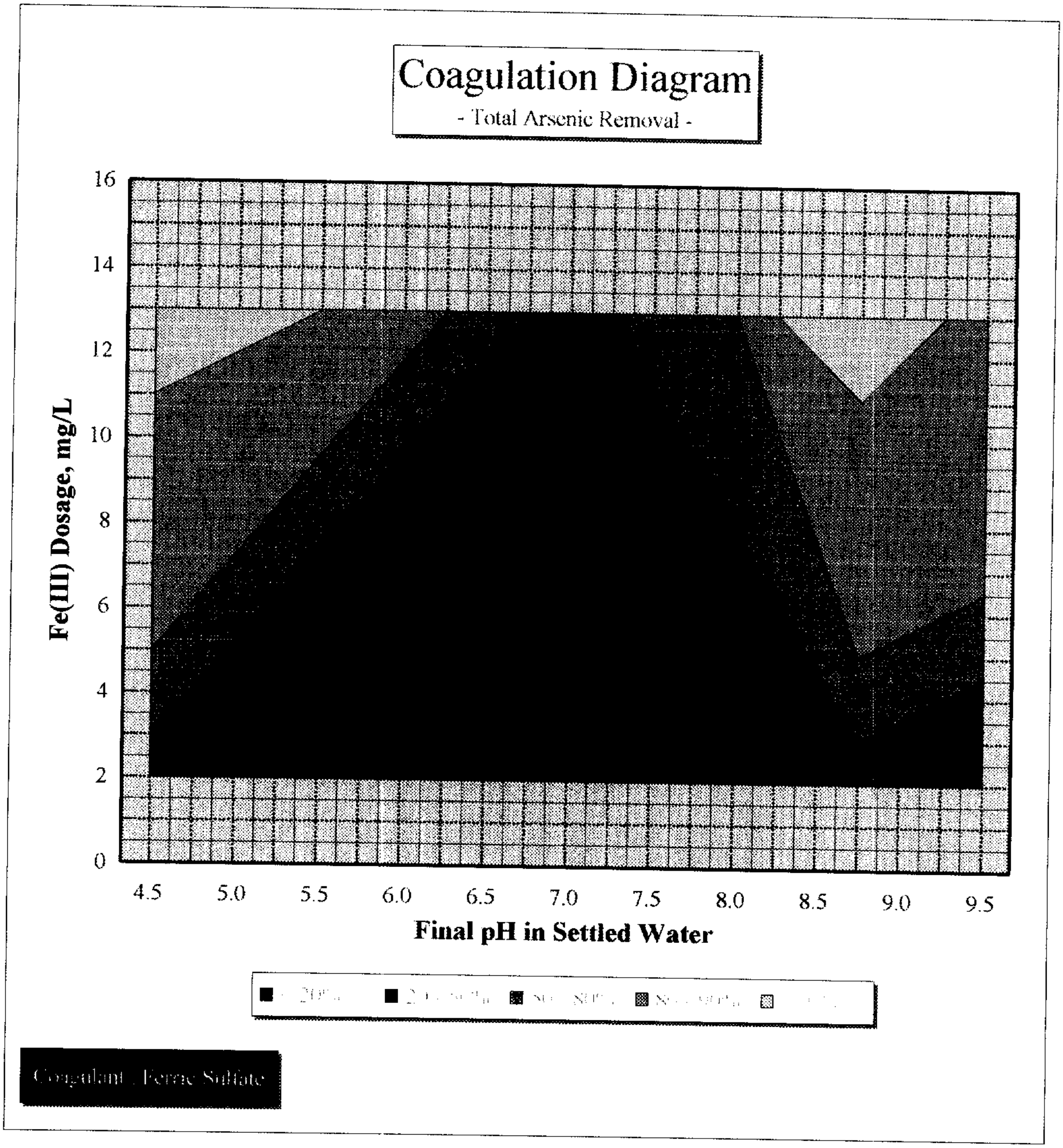

FIGURE 4-3
Coagulation Diagram for Total Arsenic Removal in the Settled Water
with Ferric Sulfate Coagulation

8.5 - 9, and at an Fe(III) dosage higher than 6 mg/L as Fe(III). The highest removal (>90 percent) was also observed at the favorable pH values and at the highest Fe(III) dosage of 12.6. It was also noted that almost no removal of total arsenic occurred in the pH range of 6 - 7.5 when the applied Fe(III) dosage was lower than 8 - 10 mg/L.

The coagulation diagrams for total arsenic removal and turbidity removal were compared. The poorest pH range for turbidity removal was exactly the same as that for total arsenic removal. This implies that poor settling may be the reason for poor removal of both constituents. In other words, the dependence of total arsenic removal upon separation of small suspended particles causing turbidity in coagulated water is clear. Figure 4-4 shows the relationship between total arsenic removal and turbidity removal. The data were grouped in accordance with the final pH conditions under which the jar tests were conducted. The departure of data points from the rest at pH 6 - 7 can obviously be seen in the plot. Removal of both targeted contaminants is affected significantly in the range of pH 6 - 7. The impact of pH on total arsenic removal, however, seems less than that on turbidity. This implies that pH conditions may influence the removal of turbidity directly, followed by the removal of total arsenic. The effect of pH on total arsenic removal, therefore, is indirect. In other coagulation research, arsenic removal was also observed to have minimum efficiency at pH 6 (Hering et al. 1996).

Slightly decreased total arsenic removal was observed under partial softening conditions. This decrease may be due to the decreased turbidity removal.

The coagulation diagram for dissolved arsenic removal in settled water is shown in Figure 4-5. Higher than 80 percent removal of initial dissolved arsenic dominated almost the whole test matrix. Since the detection limit for dissolved arsenic was 2 μg/L, higher removal rates were expected in most jar tests. This observation about dissolved arsenic removal is important because it signifies the independence of dissolved arsenic removal from total arsenic removal or turbidity. From this observation, it can be concluded that most of the initial dissolved arsenic can be converted into particulate forms of arsenic, irrespective of removal by sedimentation. Two major steps involved in arsenic removal by coagulation are (1) soluble arsenic "immobilization" and (2) separation of arsenic-carrying particles. The details about these steps will be discussed in a later section of this report. The removal of total arsenic is influenced by the efficiencies of both steps. However, it is likely that the removal of dissolved arsenic is mainly controlled by the immobilization mechanisms occurring in the first step. Therefore, removal of dissolved arsenic is a little less complicated than total arsenic removal. In other words, the coagulation diagram for dissolved arsenic removal is simpler than that for total arsenic removal.

A little drop in the removal rate of dissolved arsenic was observed at a pH of approximately 8.0 - 9.5 and a coagulant dosage lower than 4.2 mg/L as Fe(III). The lowest removal rate was about 75 percent. The reason for decreased dissolved arsenic removal in this pH range may be because the charge reverses from positive to negative on the surface of the amorphous ferric hydroxide precipitates. The z.p.c. iron oxide has been reported to occur at a pH of approximately 8.5 (Breeuwsma and Lyklema 1973). This result is consistent with the observation reported by Gulledge and O'Connor (1973). In that work, a decreased adsorption of arsenic was observed at a pH of around 8.

At pH values lower than 8.0, the predominant arsenic species are negatively charged $H_2AsO_4^-$ and $HAsO_4^{2-}$. The surface charge of amorphous ferric hydroxide precipitates maintains a positive sign. Because of the increased electrostatic interactions, the adsorption of negatively charged arsenic species on the oppositely charged surface of the amorphous ferric hydroxide precipitates may be promoted. In this pH range, the binuclear bridging complexes (Fe-O-As-O-Fe) may also be formed by the replacement of A-type surface hydroxyls (one coordinated to Fe^{3+}) with arsenic species. The formation of binuclear bridging complexes has been found in the adsorption of phosphate and sulfate on a variety of iron oxides, including α-FeOOH, β-FeOOH, γ-FeOOH, α-Fe_2O_3, and $Fe(OH)_3$ (Atkinson et al. 1974; Breeuwsma and Lyklema 1973; Hingston, et al. 1967; Huang 1975; Parfitt and Smart 1977; Parfitt et al. 1976; Russell et al. 1974; and Russell et al. 1975). This proposed mechanism was considered directly applicable to the adsorption of arsenate (Russell et al., 1975). Elkhatib et al. (1984a, 1984b) have also discussed the possibility of using similar mechanisms to describe the adsorption of arsenite on the surface of soil particles. The formation of binuclear bridging complexes is strongly dependent upon pH. In general, lowering pH values

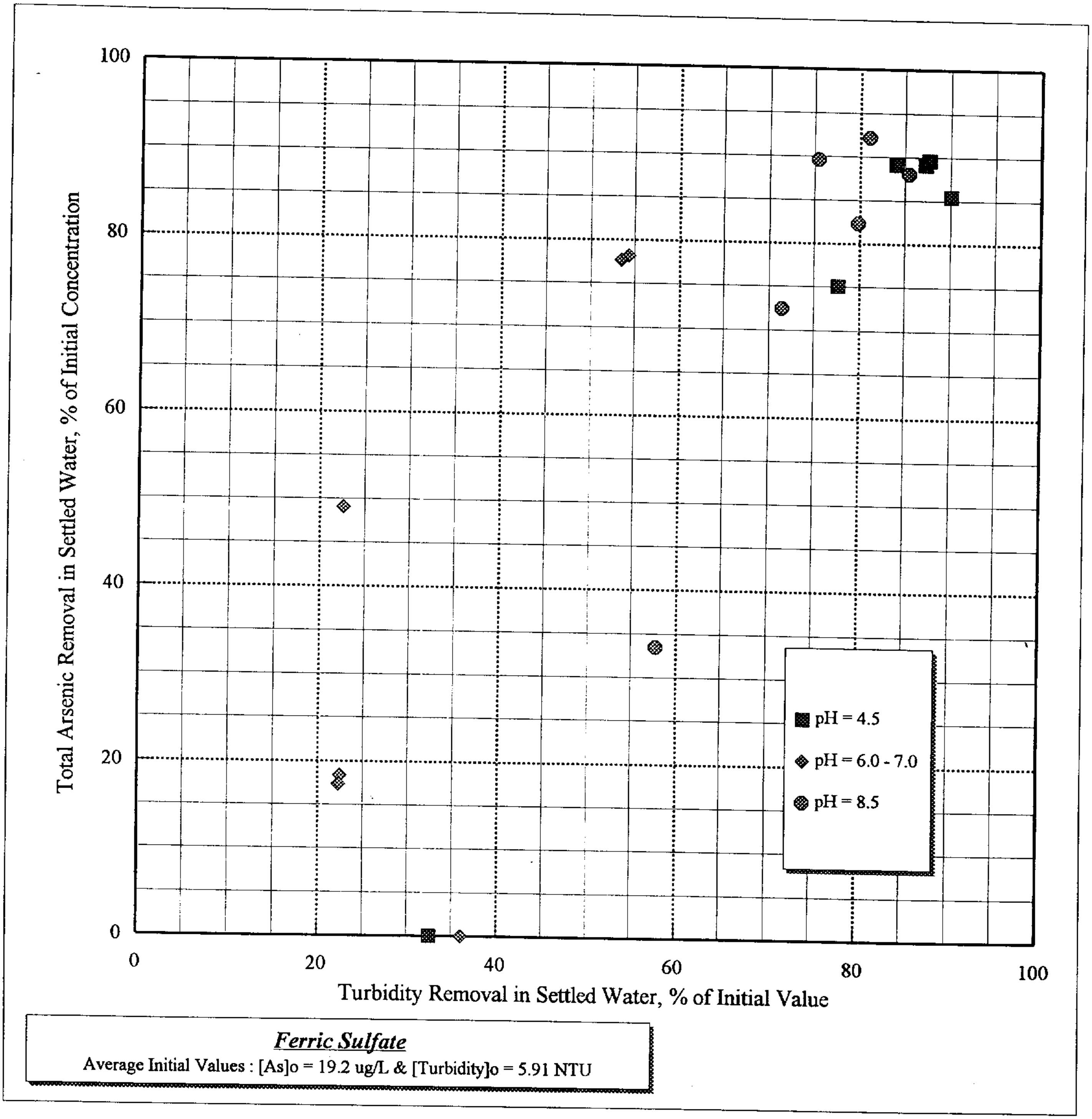

FIGURE 4-4

Relationship Between Arsenic Removal and Turbidity Removal in Settled Water with Ferric Sulfate Coagulation

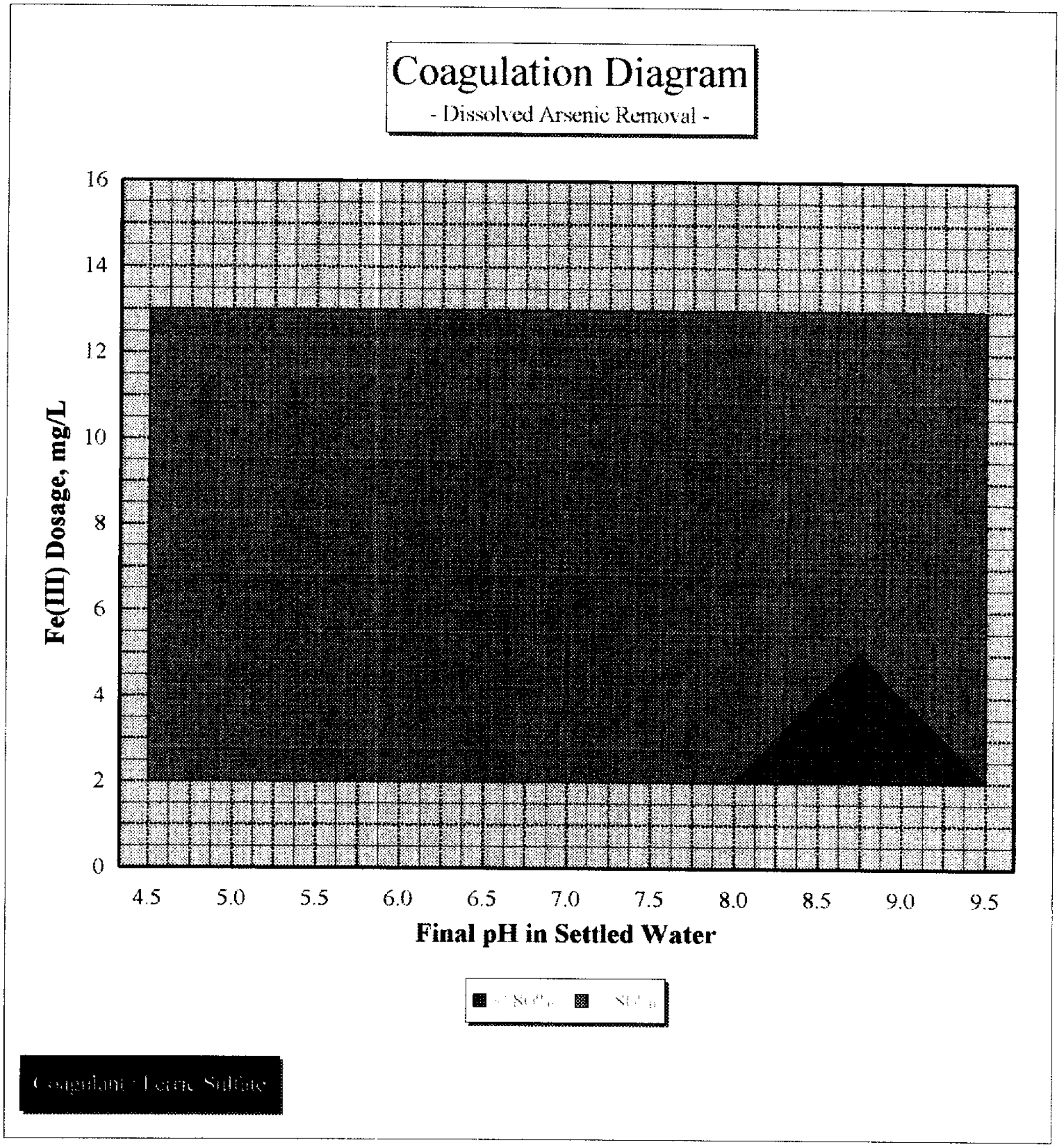

FIGURE 4-5
Coagulation Diagram for Dissolved Arsenic Removal in Settled Water
with Ferric Sulfate Coagulation

encourages formation potential of binuclear bridging. On the other hand, the formation of an open card-house structure at a lower pH (< 6) may further enhance the removal of particulate forms of arsenic in the particle separation step (Step 2). Therefore, better efficiency of arsenic removal is expected at a lower pH. This conclusion is supported by observation of total arsenic removal under low pH conditions (Figure 4-3).

At pH values higher than 9.0, the surface of amorphous ferric hydroxide precipitates is usually negatively charged. When lime ($Ca(OH)_2$) is added, however, a surface charge reverse may happen even at a high pH because of the adsorption of calcium cations (Ca^{2+}) on the surface of amorphous ferric hydroxide precipitates (Wilkie and Hering 1996). The positively charged surface may again be suitable for the adsorption of negatively-charged $HAsO_4^{2-}$ that is the predominant arsenic species in water in the pH range of 8.0 - 11.0. The removal of arsenic may therefore be improved slightly. Since there is no chance of forming binuclear bridging complexes, this improvement in the efficiency of arsenic removal would be limited. A similar observation has been reported in another study (Hering et al. 1996).

Organic Carbon Removal

TOC removal by coagulation, with ferric sulfate as the primary coagulant, is presented in Figure 4-6. It is clear that TOC can be removed effectively (>40 - 70 percent) only at an Fe(III) dosage in excess of 8 mg/L and a pH below 6.5. The best removal (> 70 percent) was achieved at a pH of about 5 - 6 and at the highest Fe(III) dosage of 12.6 mg/L. At a pH of 7.5 - 9, poor TOC removal (<20 - 40 percent) was observed irrespective of Fe(III) dosage (up to 12.6 mg/L). This pH range is clearly the worst condition for TOC removal.

By comparing the coagulation diagrams for TOC removal with those for other constituents obtained so far, it is noted that the shape of the coagulation diagram for TOC removal differs from that for either turbidity or arsenic removal. Two important observations on TOC removal are that (1) the final pH value was a more significant condition than the coagulant dosage and that (2) the sweep-coagulation mode was not very effective for TOC removal. This implies that different mechanisms may dominate the removal of organic matters. The adsorption of organic carbon on amorphous ferric hydroxide precipitates may not be the major mechanism for TOC removal because of the poor stoichiometrical and thermodynamic relationship between the amount of TOC removed and the amount of coagulant applied.

The observation of improved TOC removal at a pH higher than 9 is consistent with that reported in the literature (Liao and Randtke 1985 and 1986, and Randtke 1988). It has been suggested that the calcium precipitates are generally not good adsorbents for organic substances and therefore that the removal of TOC is probably the result of the special adsorption of certain functional groups (particularly carboxyl acids) on the surface of these precipitates (Amirtharajah and O'Melia 1990).

There is a great deal of inconsistency in TOC and DOC results in many samples. Normally, the DOC values in a sample are expected to be lower than the corresponding TOC measurements. Many DOC results, however, are higher than the TOC values. These results are shown in Figure 4-7. The reversal of DOC and TOC data cannot be fully explained; but it may be the result of (1) the possible contamination of the samples during the filtration step, if filter preparation is insufficient and (2) inconsistency or an experimental error because the TOC and DOC values are being too close.

Reduction in UV254 Absorbance

Figure 4-8 presents the coagulation diagram for the reduction in UV254 absorbance in the settled water samples. In general, this diagram gives a picture similar to that for TOC removal. The results showed that the UV254 reduction was strongly pH-dependent. Effective reduction in UV254 (>60 percent) was reached at a pH lower than 6 and an Fe(III) dosage higher than 8 mg/L. The best UV254 reduction (> 70 percent) was at pH 5 and at Fe(III) dosages higher than 6 mg/L. At pH 6 - 7.5, moderate reduction (40 - 60 percent) was achieved when the coagulant dosages were higher than 8 mg/L as Fe(III). The poorest pH range for UV254 reduction was found at pH 7.5 - 9. Within this pH range, the reduction in UV254 was very low (<20 percent) at an Fe(III)

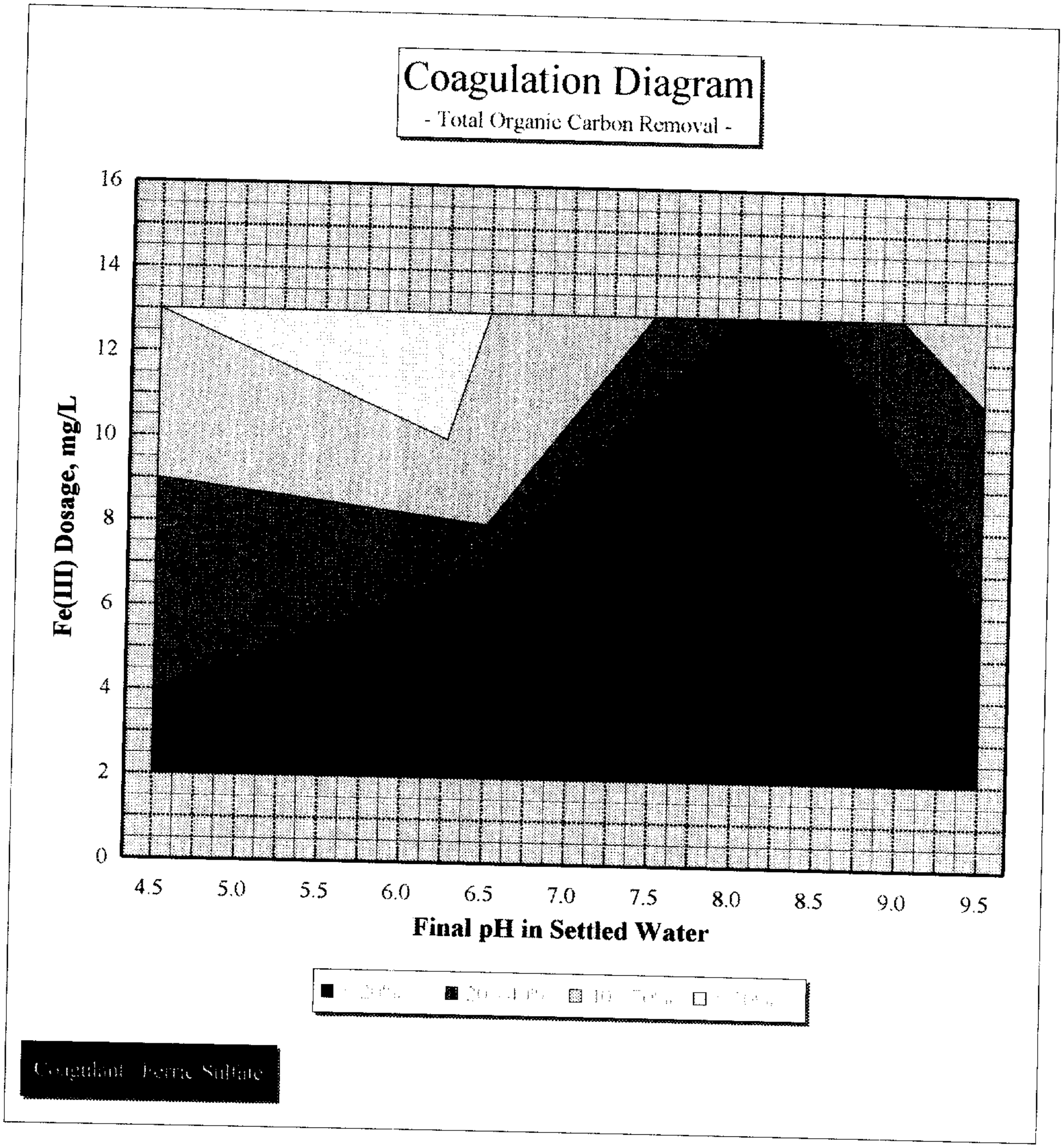

FIGURE 4-6
Coagulation Diagram for TOC Removal in Settled Water
with Ferric Sulfate Coagulation

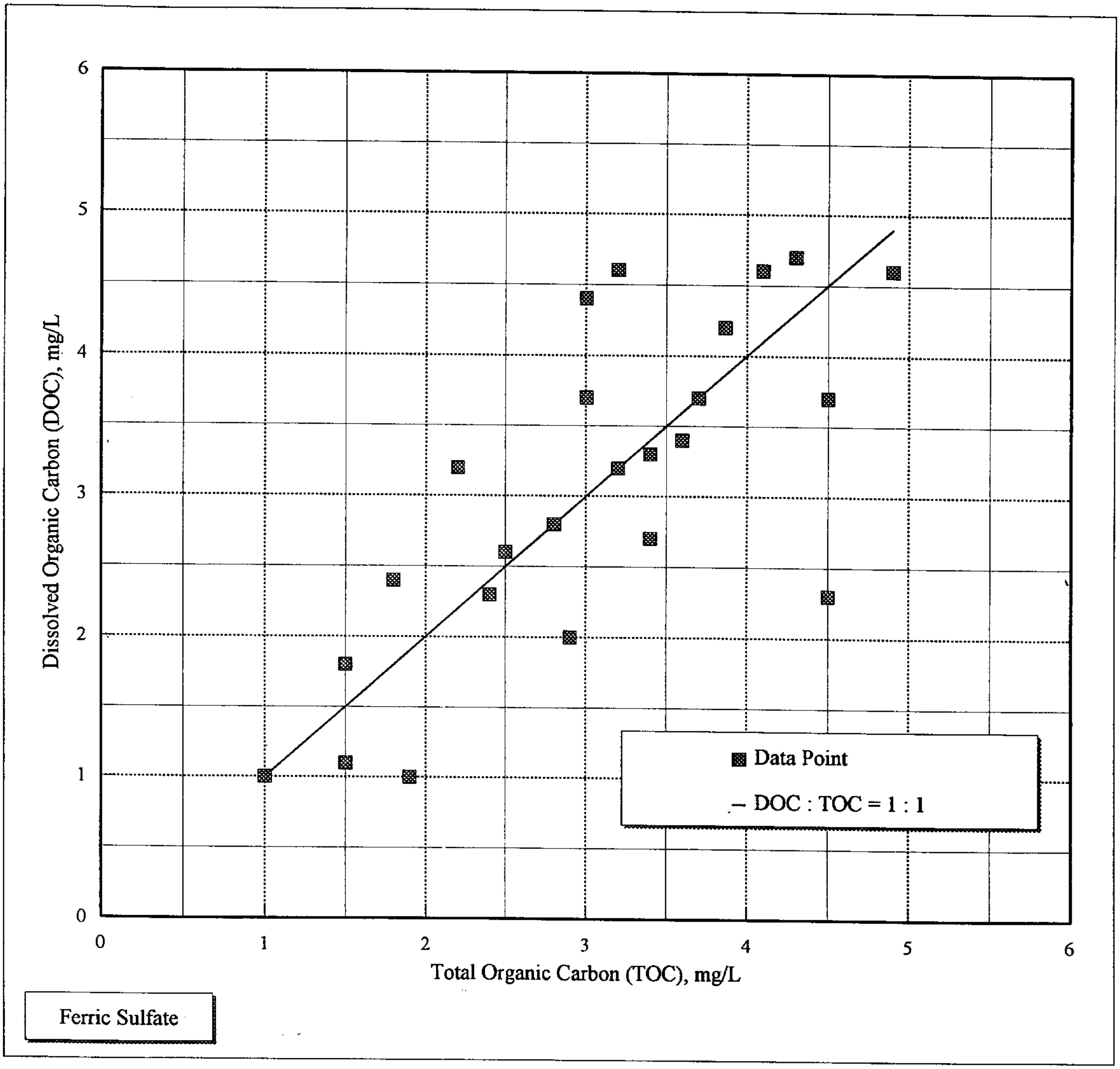

FIGURE 4-7

Plot of Total and Dissolved Organic Carbon with Ferric Sulfate Coagulation

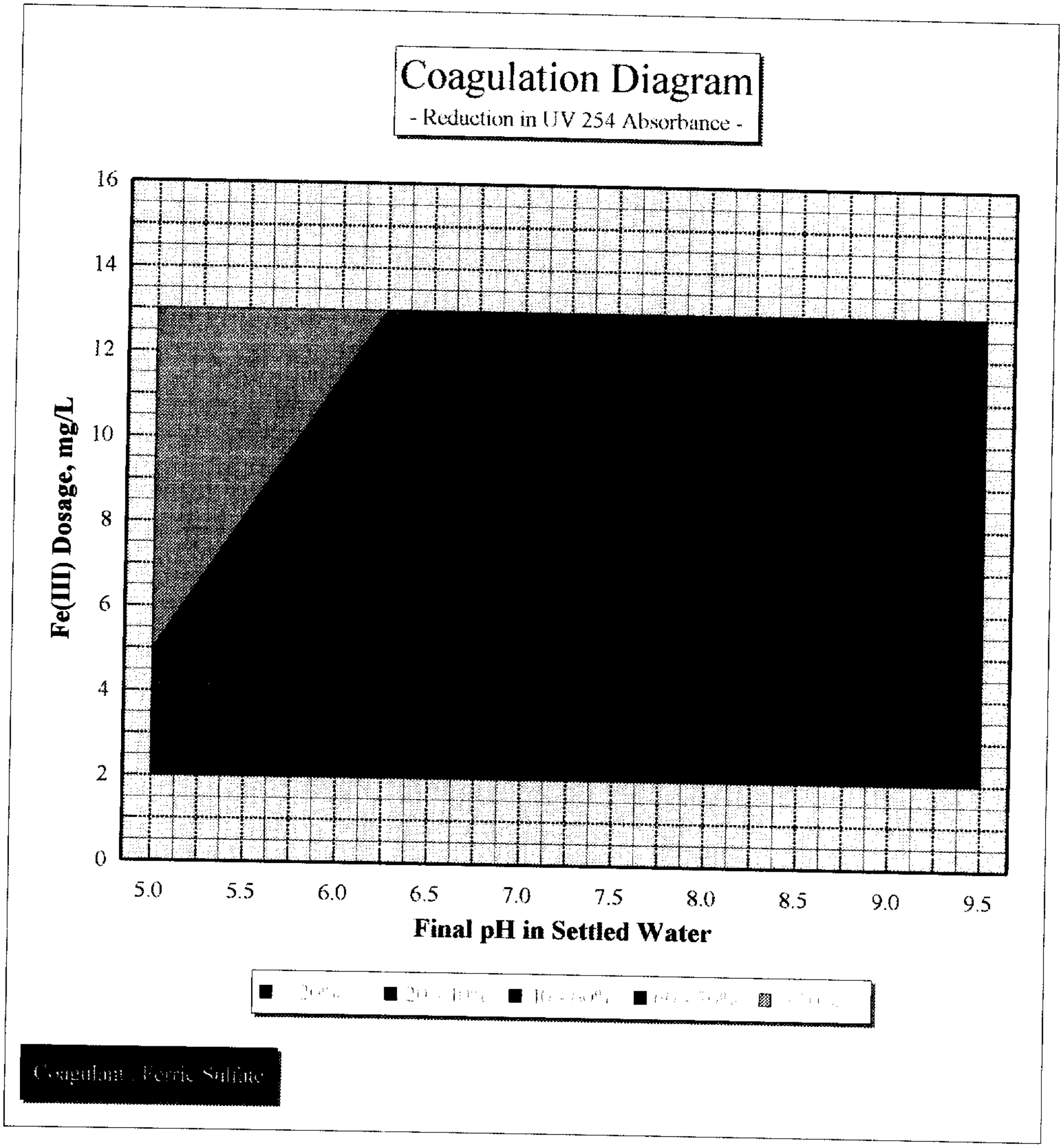

FIGURE 4-8
Coagulation Diagram for Reduction in UV254 Absorbance in Settled Water with Ferric Sulfate Coagulation

dosage below 6 mg/L. At pH > 9, the UV254 reduction was improved a little. The reduction (between 20 - 40 percent) was almost independent of the coagulant dose when the Fe(III) dosage was higher than 6 mg/L.

The consistency in the coagulation diagrams for TOC removal and reduction in UV254 absorbance implies a possible relationship between these two constituents. On the contrary, the results obtained in the jar tests did not provide a significant relationship between DOC values and UV254 absorbance. The plot of these results shows a great deal of scattering, as shown in Figure 4-9.

FERRIC CHLORIDE COAGULATION DIAGRAMS

Seven jar tests were conducted with ferric chloride coagulant under different chemical conditions. Summary information about these jar tests and the experimental data are provided, respectively, in Appendices A and B. The jar tests with ferric chloride covered a wider range of Fe(III) than those with ferric sulfate. Because the Fe(III) content in liquid ferric chloride was higher. The Fe(III) dosage was in the range of 2.8 to 16.8 mg/L, whereas the pH values ranged between 5.4 and 10.7. Figure 4-10 shows a sample grid of all experimental conditions under which each targeted constituent was tested in the experiments. Coagulation diagrams were prepared for turbidity, arsenic, TOC removals, and UV254 absorbance. The procedure for preparation of these coagulation diagrams is similar to that for ferric sulfate coagulant.

Turbidity Removal

Turbidity removals at different pH values and ferric chloride dosages are shown in Figure 4-11. The results show that excellent turbidity removal (>90 percent) is obtained at Fe(III) dosages of 11.2 mg/L or higher. There is little effect of pH on turbidity removal above this dosage. When the dosages are lower than 11.2 mg/L as Fe(III), the best and worst pH conditions for turbidity removal are about 8 - 8.5 and 6 - 6.5, respectively. At the optimum pH condition (pH = 8 - 8.5), high turbidity removal efficience (>95 percent) is easily achieved at an Fe(III) dosage as low as 6 mg/L. However, at the poorest pH value (pH = 6 - 6.5), very poor removal of turbidity (<50 percent) was observed even at an Fe(III) dosage of 6 mg/L. Good turbidity removal (>90 percent) was also achieved under partial softening conditions (20 - 40 percent hardness removal) when lime was added to raise the pH to approximately 10.5.

By comparing the coagulation diagram prepared with ferric chloride and that prepared with ferric sulfate, four important observations can be made (1) a similar trend of turbidity removal, (2) less pH dependence with ferric chloride, (3) higher turbidity removal with ferric chloride at the same Fe(III) dosage, and (4) slightly improved turbidity removal around pH 10.5 with ferric chloride.

The reason for less pH dependence and high coagulation effectiveness with affected ferric chloride cannot be explained clearly. One of the possible reasons may be the effect of anions, e.g., sulfate (SO_4^{2-}) and chloride (Cl^-). Hunter (1987) reported possible reasons of why counter-ions on the coagulation behaviors of $Fe(OH)_3$ sol. The effect of Cl^- on the formation of Fe(III) oxyhydroxide was also observed by Dousma, et al. (1978).

Better turbidity removal at pH 10.5 than at pH 9 with lime may possibly be the result of magnesium hydroxide precipitation. This mechanism was described by Amirtharajah and O'Melia (1990) as the typical sweep coagulation and is usually effective at a pH value of 11.0 - 11.3 (ASCE and AWWA 1990). However, it is possible that magnesium hydroxide precipitation may occur at a lower pH. It has been reported that maximum calcium carbonate precipitation may occur at pH as low as 9.3 in actual operation because of this shift (James M. Montgomery, 1985).

Arsenic Removal

The coagulation diagram for total arsenic removal in settled water is shown in Figure 4-12. Higher than 90 percent removal of initial total arsenic was achieved at Fe(III) dosages higher than 11.2 mg/L, irrespective of the final pH. The detection limit of total arsenic is 1 μg/L; therefore, arsenic removal efficiencies higher than 95 percent could not be distinguished. It is anticipated that higher removal of total arsenic may be obtained at Fe(III) dosages above 14 mg/L. The effective pH range for low coagulant dosages was between 8 and 8.5. In this range, 90 percent total arsenic removal

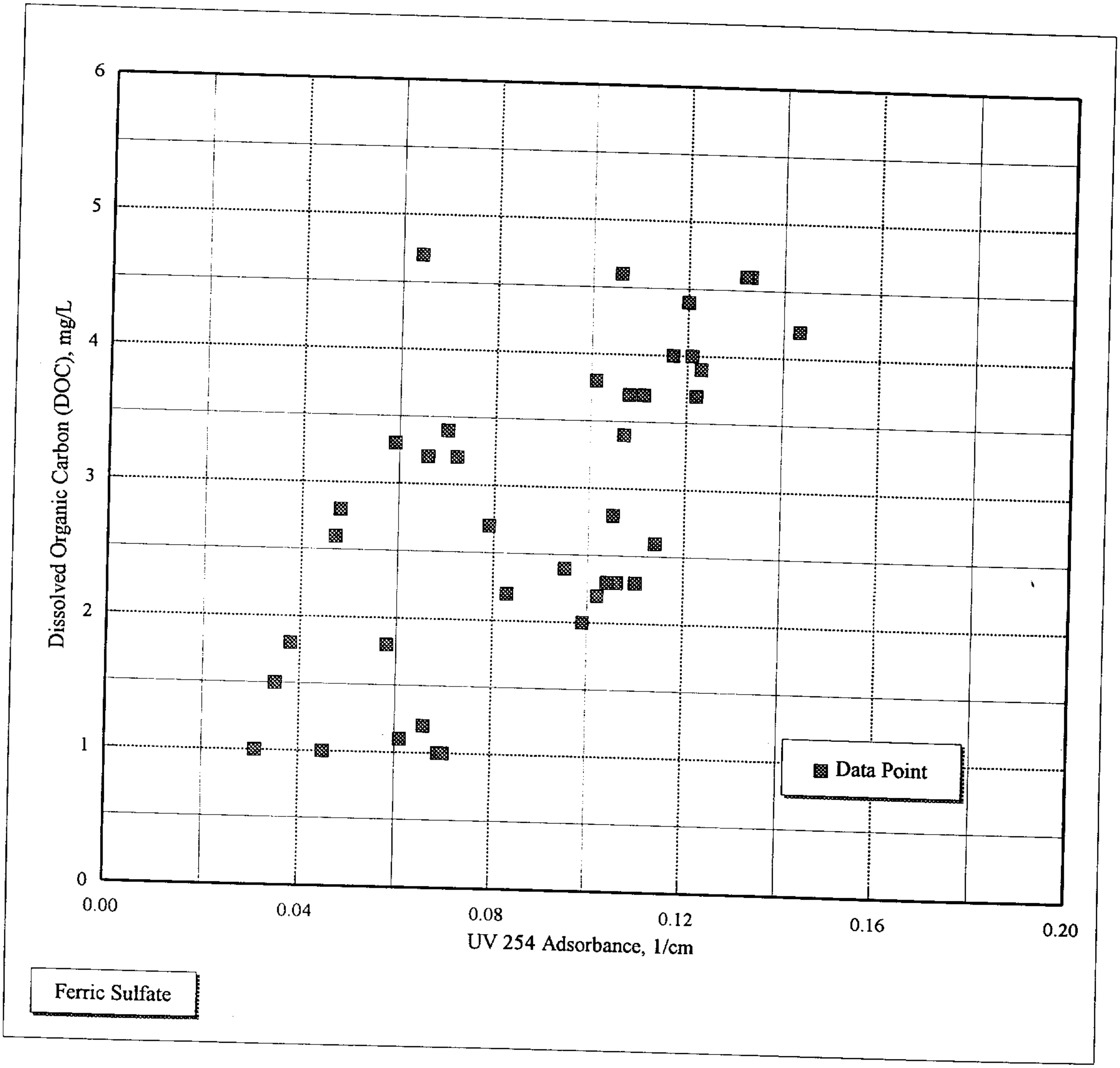

FIGURE 4-9

Plot of Dissolved Organic Carbon and UV254 with Ferric Sulfate Coagulation

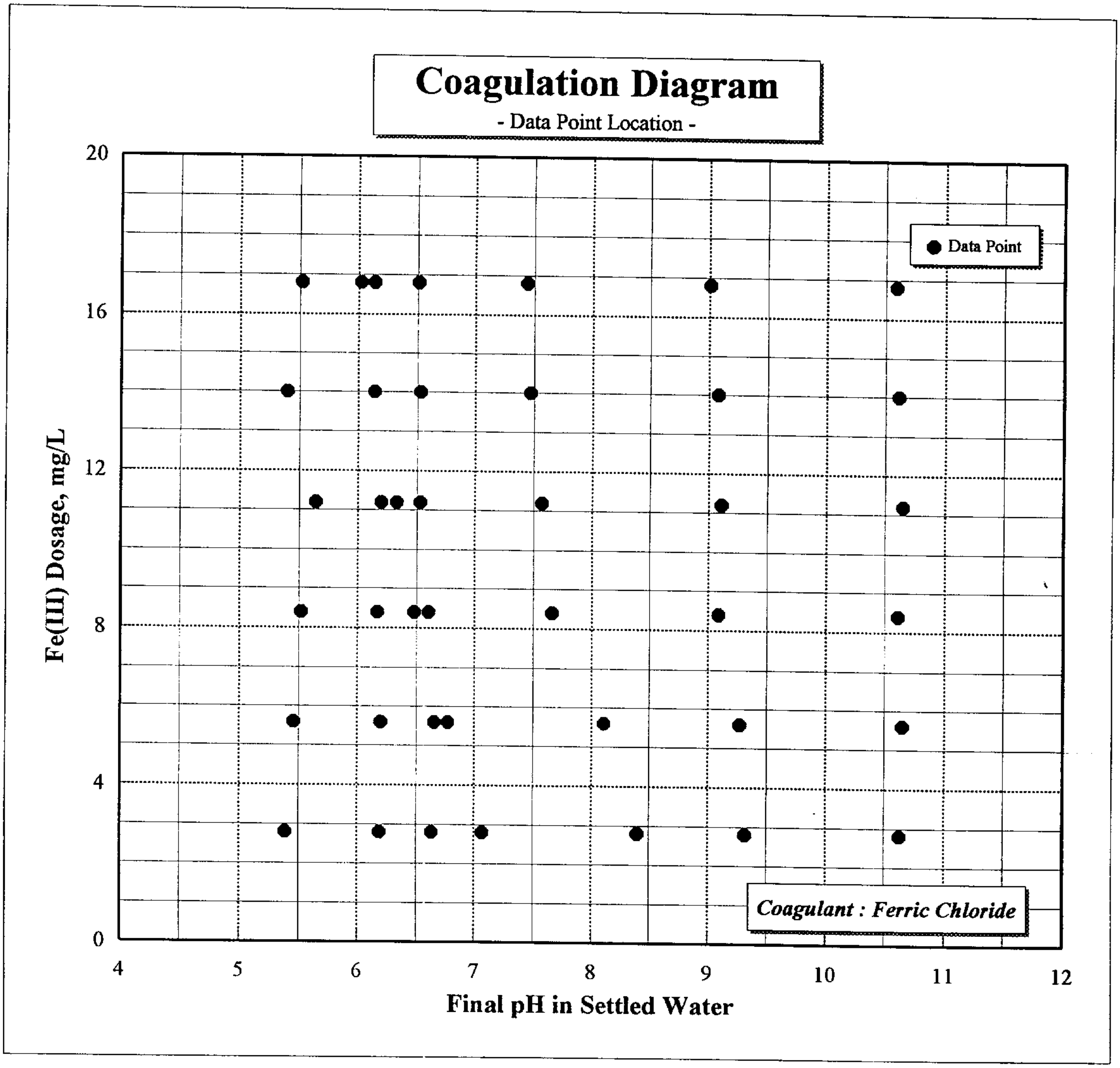

FIGURE 4-10

Sample Data Point Locations for Preparation of
Coagulation Diagrams with Ferric Chloride

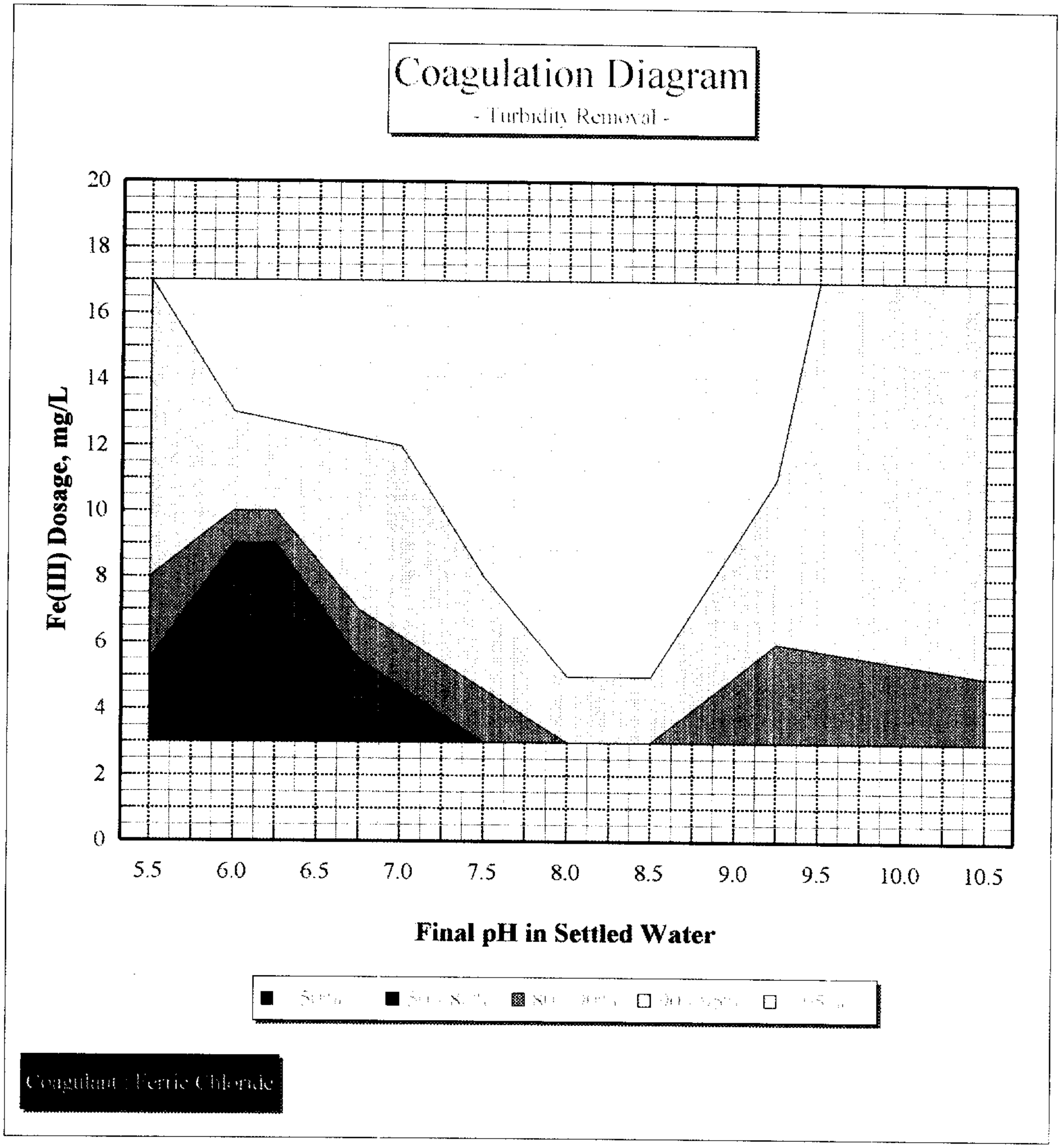

FIGURE 4-11
Coagulation Diagram for Turbidity Removal in Settled Water
with Ferric Chloride Coagulation

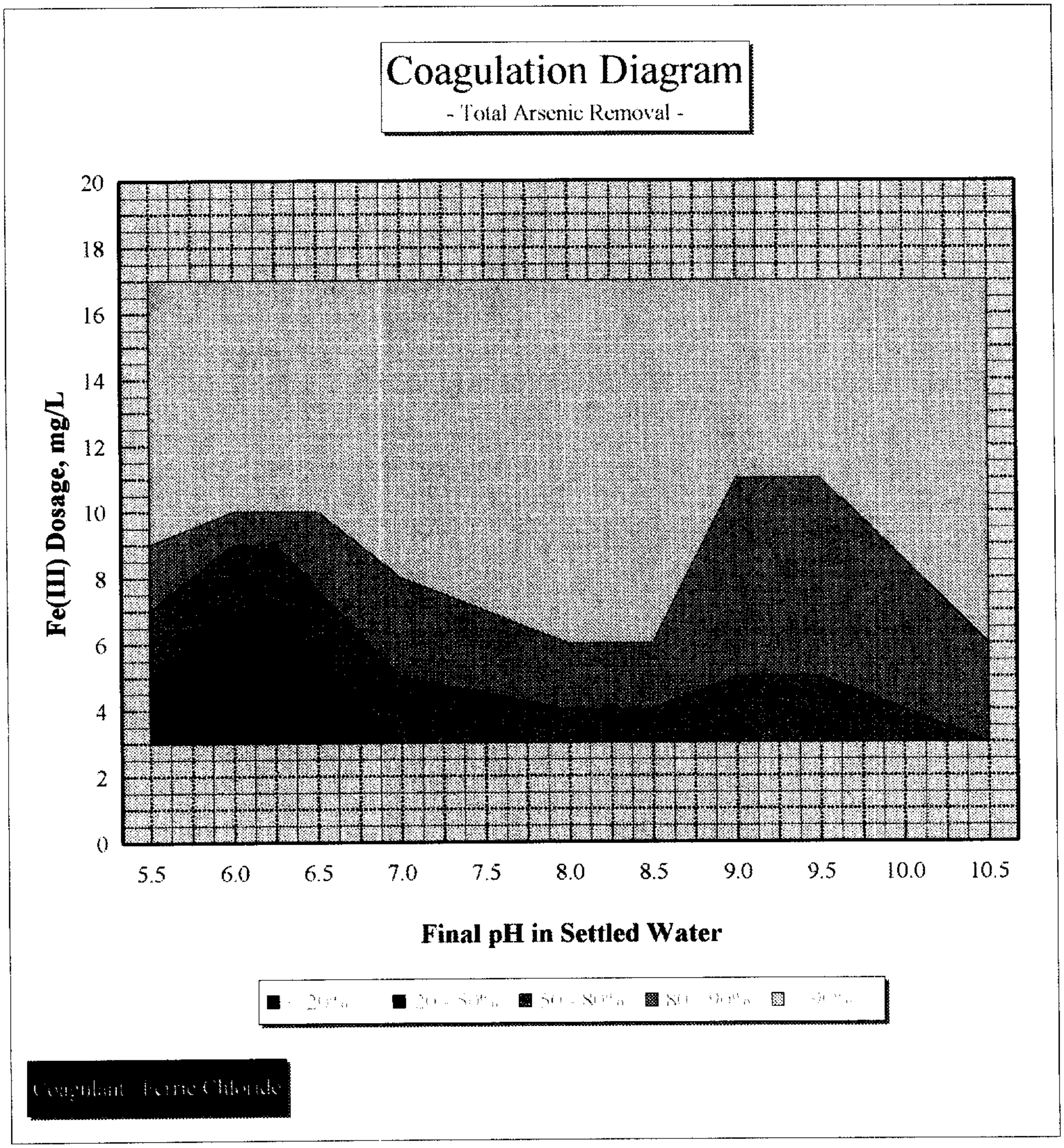

FIGURE 4-12
Coagulation Diagram for Total Arsenic Removal in Settled Water
with Ferric Chloride Coagulation

was observed at an Fe(III) dosage of 8.4 mg/L. With partial softening, the removal of arsenic was also improved significantly. Total arsenic removal as high as 80 percent was obtained at pH 10.5 and at an Fe(III) dosage as low as 2.8 mg/L as Fe(III). The poorest pH for arsenic removal occurred in a narrow pH range of around 6.

At pH above 9.5, increased removal of total arsenic may be due to (1) favorable conditions for adsorption of arsenic species because of the presence of calcium cations (Wilkie and Hering 1996), (2) the enhanced removal of arsenic-carrying amorphous ferric hydroxides by the electrostatic attractions between the negatively charged calcium carbonate precipitations (Amirtharajah and O'Melia 1990) and the positively charged amorphous ferric hydroxide precipitates (Wilkie and Hering 1996), and (3) improved turbidity removal by sweep coagulation by formation of amorphous magnesium hydroxide precipitates (Amirtharajah and O'Melia 1990).

The removal trend for total arsenic removal in general is similar to that for turbidity. Therefore, the discussion of the coagulation diagram for turbidity removal given in an earlier section also applies to total arsenic removal. A plot of percents of total arsenic and turbidity removals in settled water is shown in Figure 4-13. Clearly, there is less pH dependence for both turbidity and total arsenic removals. This is an important relationship between these two constituents.

The coagulation diagram for dissolved arsenic removal could not be prepared for ferric chloride coagulation because of data inconsistency.

Organic Carbon Removal

Poor TOC removal was observed with ferric chloride. The results are presented in Figure 4-14. TOC removal less than 40 percent is the predominant area in the coagulation diagram in particular, the region above pH 7. Higher than 40 percent TOC removal was obtained only in a small region covered by pH 5.5 - 6.5 and a coagulant dosage above 14 mg/L as Fe(III). Although the general trend of TOC removal with ferric chloride was similar to that obtained with ferric sulfate, the overall efficiency of TOC removal with ferric chloride was lower. The reason for the poor performance of ferric chloride in removing TOC is not clearly known. There was a great deal of data inconsistency between TOC removal and the Fe(III) dosage applied. Insufficient sampling, storage, and analysis may have contributed to this inconsistency.

Reduction in UV254 Absorbance

Figure 4-15 shows the reduction in UV254 absorbance in settled water with ferric chloride. Good reduction in UV254 (>40 percent) was achieved under all pH conditions as long as Fe(III) dosages were higher than 11.2 mg/L. The best UV254 reduction (70 - 80 percent) was found at pH 5.5 even at an Fe(III) dosage of 6 mg/L. Another good pH condition for UV254 reduction was around pH 9. The poorest conditions for the reduction of UV254 absorbance were in the pH range of 7 - 8.5. Very poor reduction was observed in this range when Fe(III) dosages were below 8.4 mg/L as Fe(III). At around pH 10 - 10.5, coagulation in conjunction with partial softening (20 - 40 percent hardness removal) is not as effective for UV254 reduction as that for arsenic removal. This ineffective reduction in UV 254 absorbance was unexpected, as the removal of organic substances should be enhanced by an increase of pH and formation of a large number of calcium carbonate and magnesium hydroxide precipitates (Liao and Randtke 1985, and Randtke 1988).

ALUM COAGULATION

Two jar tests were conducted with alum at pH 5.5 and at natural pH. The alum dose ranged from 1.7 to 10.1 mg/L as Al(III). Summary information about these jar tests and the experimental data are provided, respectively, in Appendices A and B. In general, the results of alum coagulation on each constituent followed the same trend as those with iron-based coagulants. These results are presented below.

Turbidity Removal

Turbidity removal results with alum coagulation are shown in Figure 4-16. It may be noted that turbidity removals in the range of 93 - 94 percent were consistently maintained with no pH

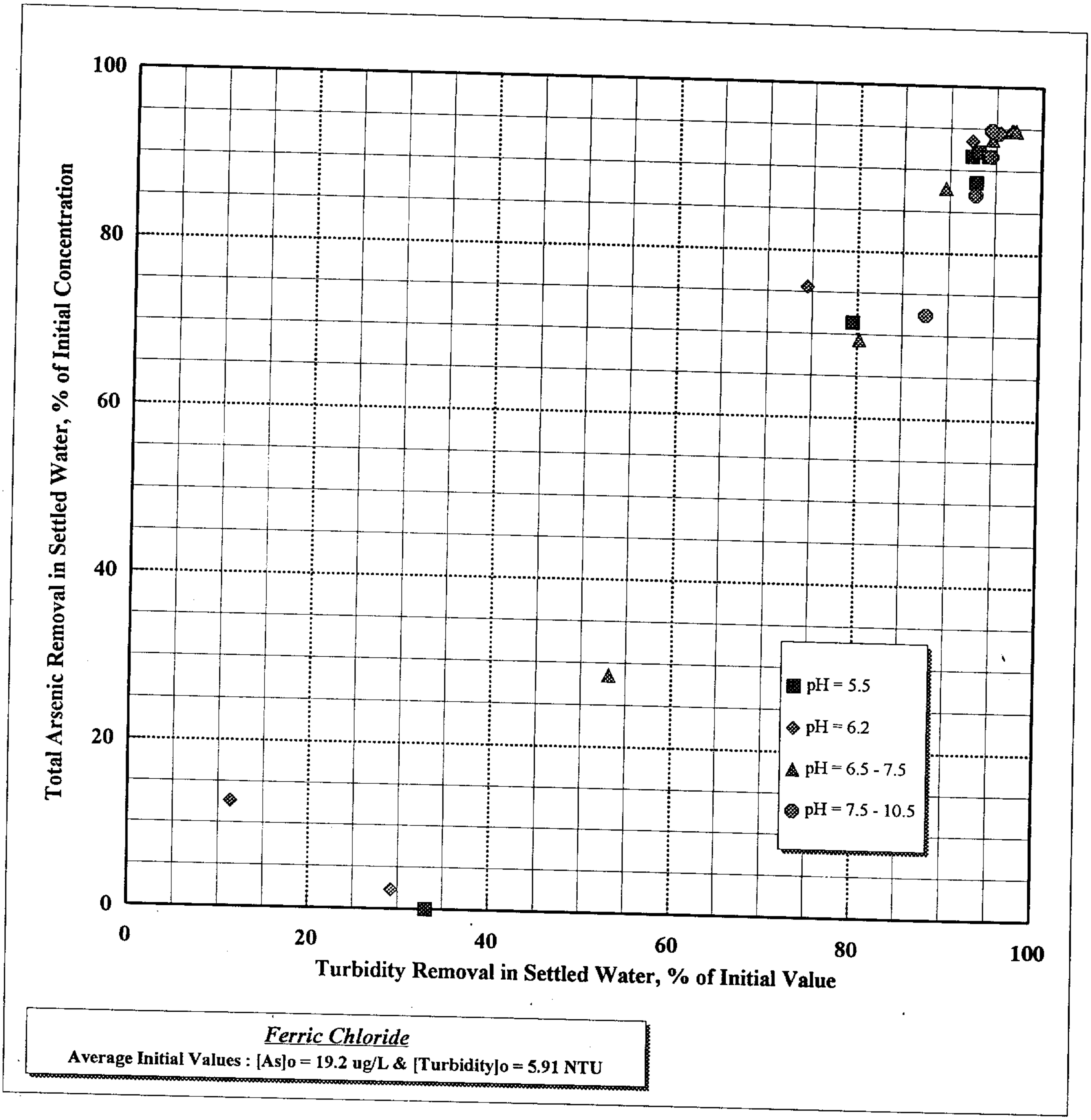

FIGURE 4-13

Relationship Between Arsenic Removal and Turbidity Removal in Settled Water with Ferric Chloride Coagulation

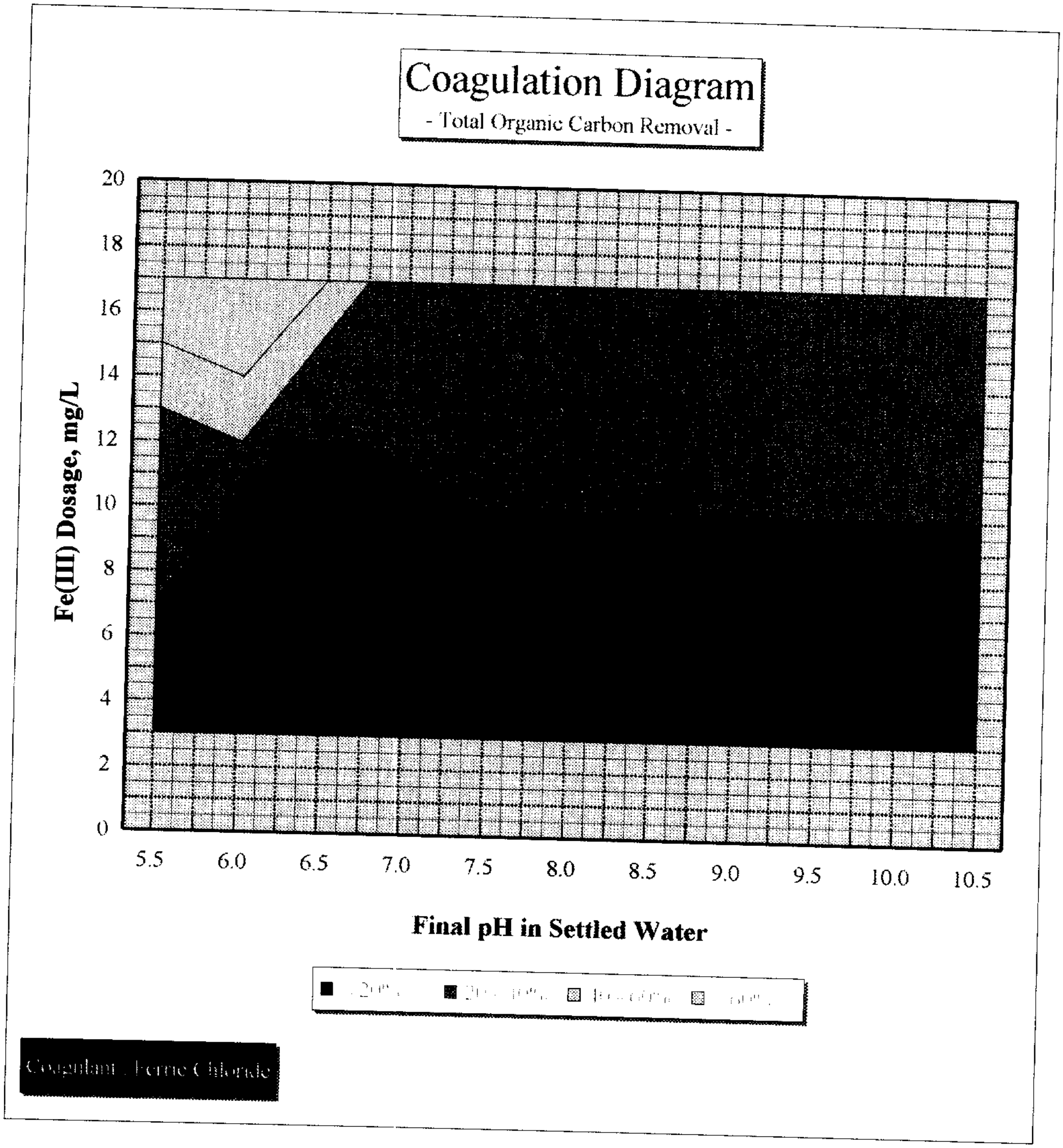

FIGURE 4-14
Coagulation Diagram for TOC Removal in Settled Water
with Ferric Chloride Coagulation

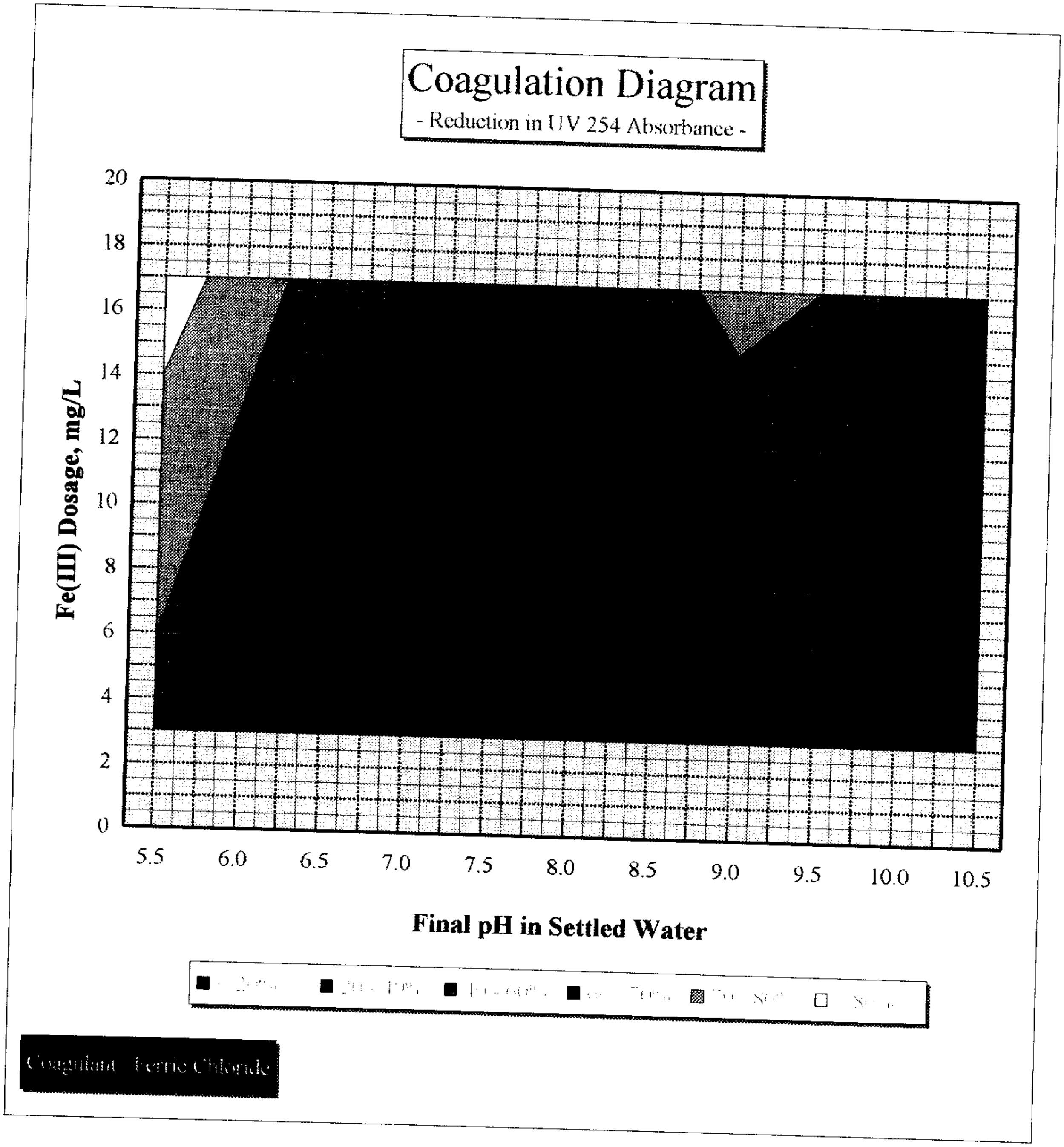

FIGURE 4-15
Coagulation Diagram for Reduction in UV254 Absorbance in Settled Water with Ferric Chloride Coagulation

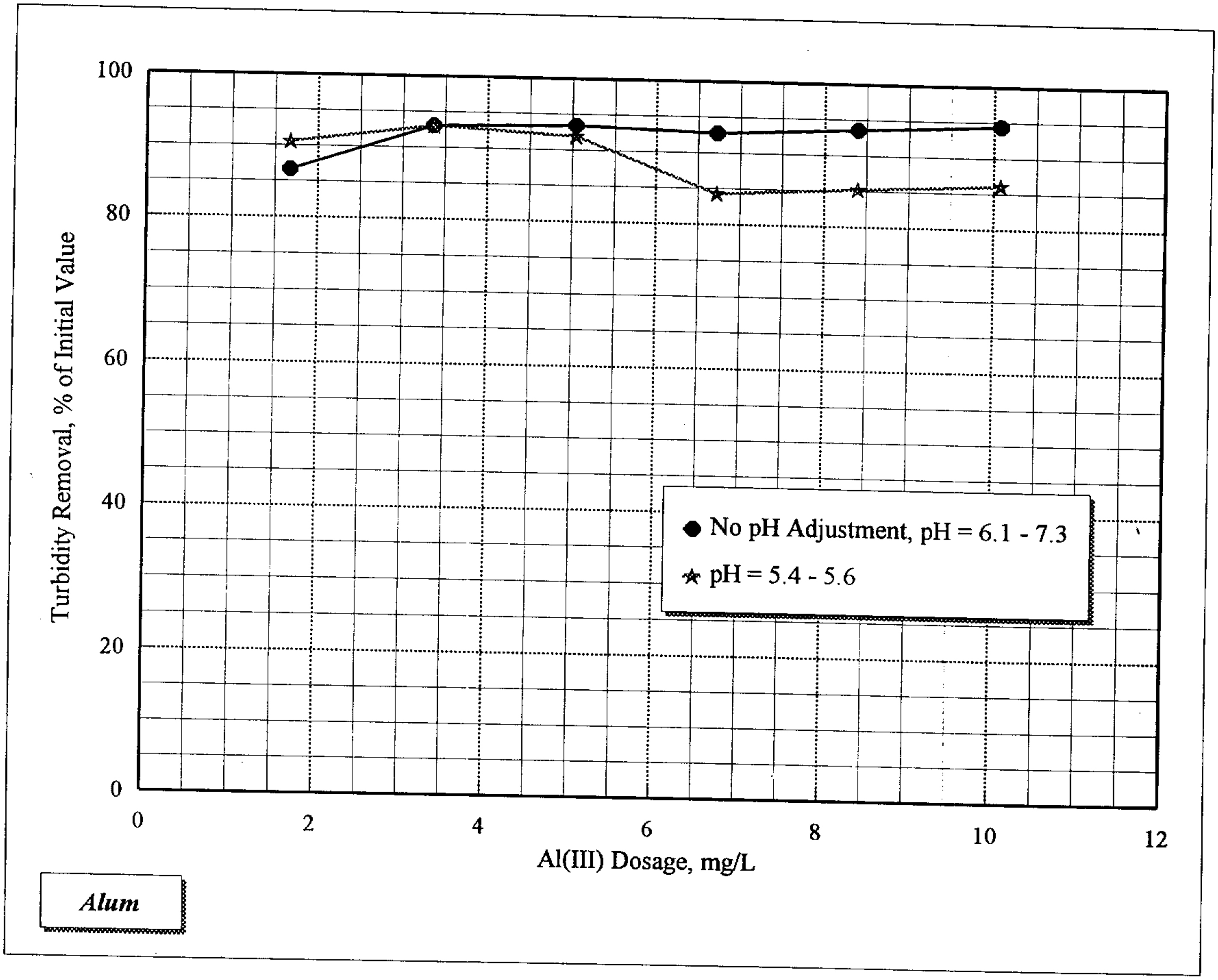

FIGURE 4-16

Experimental Results of Turbidity Removal with Alum Coagulation adjustment and at Al(III) doses higher than 3.4 mg/L. On the other hand, turbidity removal at pH 5.5 was greatly influenced by the Al(III) dose. Optimum removal was 93 percent at an Al(III) dose of 5 mg/L. The turbidity removal subsequently decreased slightly at higher alum dosages. It is likely that alum coagulation for turbidity removal is more effective without pH adjustment because the sweep-coagulation would happen under this pH condition (Amirtharajah and Mills 1982).

Arsenic Removal

The results of total arsenic removal with alum coagulant are shown in Figure 4-17. Under both pH conditions, arsenic removal in the range of 87 - 94 percent was observed at an Al(III) dosage higher than 5 mg/L. An optimum removal of 94 percent was achieved at an Al(III) dosage of 6.7 - 8.4 mg/L and without pH adjustment. In general, alum coagulation for total arsenic removal was less effective than an iron-based coagulant (Figure 4-3 and 4-12). This observation is consistent with that reported in the literature (Sorg and Logsdon 1978).

Organic Carbon Removal

A few data points of TOC removal with alum were obtained (Figure 4-18). Poor removal was observed under both operational conditions. The best TOC removal (about 50 - 55 percent) was achieved at Al(III) dosages of 5 - 6.7 mg/L. Therefore, lower pH seems to be favorable for TOC removal. This is consistent with the results for iron-based coagulants (Figures 4-6 and 4-14).

Reduction in UV254 Absorbance

The results of reduction in UV254 absorbance for alum coagulation are shown in Figure 4-19. Coagulation with alum at a lower pH (5.5) shows better reduction in absorbance than that without pH adjustment. The reduction rates of 67 - 70 percent were observed at a dosage higher than 3.4 mg/L as Al(III). However, the reduction in UV254 absorbance without pH adjustment shows more dependence on Al(III) dosage than that at pH 5.5. These observations on alum coagulation are consistent with those on iron-based coagulation (Figures 4-8 and 4-15).

4.3.2 PREOZONATION

Arsenic removal by coagulation processes is generally dependent upon the predominant species. As(V) and As(III) exhibit entirely different removal behaviors (Hering et al., 1996; Jekel 1994 and Sorg and Logsdon 1978). Under similar coagulation conditions, As(V) removal is significantly higher than that for As(III). For this reason, numerous studies have been conducted in conjunction with the oxidation of As(III) to As(V). A variety of oxidants has been used by others. In this study, preozonation as a means to oxidize As(III) and then to improve its removal was investigated; significant improvement in As(III) removal after preozonation was observed. The results of As(III) removal with and without preozonation are compared and discussed below.

REMOVAL OF As(III) WITHOUT PREOZONATION

A raw water sample was freshly prepared by spiking it with As(III). The initial total arsenic concentration was measured, and the average value was 10.5 μg/L. Two jar tests were conducted, one with ferric chloride and the other with ferric sulfate. No pH adjustment was made in either experiment. The final pH values with ferric chloride were in the range of 6.8 to 7.3. The results of As(III) removal are shown in Figure 4-20. In general, total arsenic removal increased by increasing the coagulant dosage. At Fe(III) dosages higher than 8.4 mg/L, about 65 - 80 percent total arsenic removal was observed. Sorg and Logsdon (1978) reported As(III) removal efficiency of only about 55 percent at an Fe(III) dosage of 5 mg/L and pH of 7. This value compares very well with As(III) removal at an Fe(III) dosage of 5 mg/L (Figure 4-20).

Figure 4-20 is also used to compare the removal rates of As(III) and As(V). In this figure, the experimental data for As(V) removal without preozonation were obtained from the coagulation diagram experiments. The experimental conditions for As(V) removal studies were as follows: (1) the initial total arsenic concentration in the As(V) spiked raw water sample was 19.2 μg/L, and (2) final pH values in settled water were in the range of 6.0 to 7.1. Total arsenic removal efficiencies at an Fe(III) dosage of 8.4 mg/L were higher than 80 percent. At Fe(III) dosages in excess of 8.4 mg/L, approximately 90 - 95 percent total arsenic removal was observed. A comparison of two

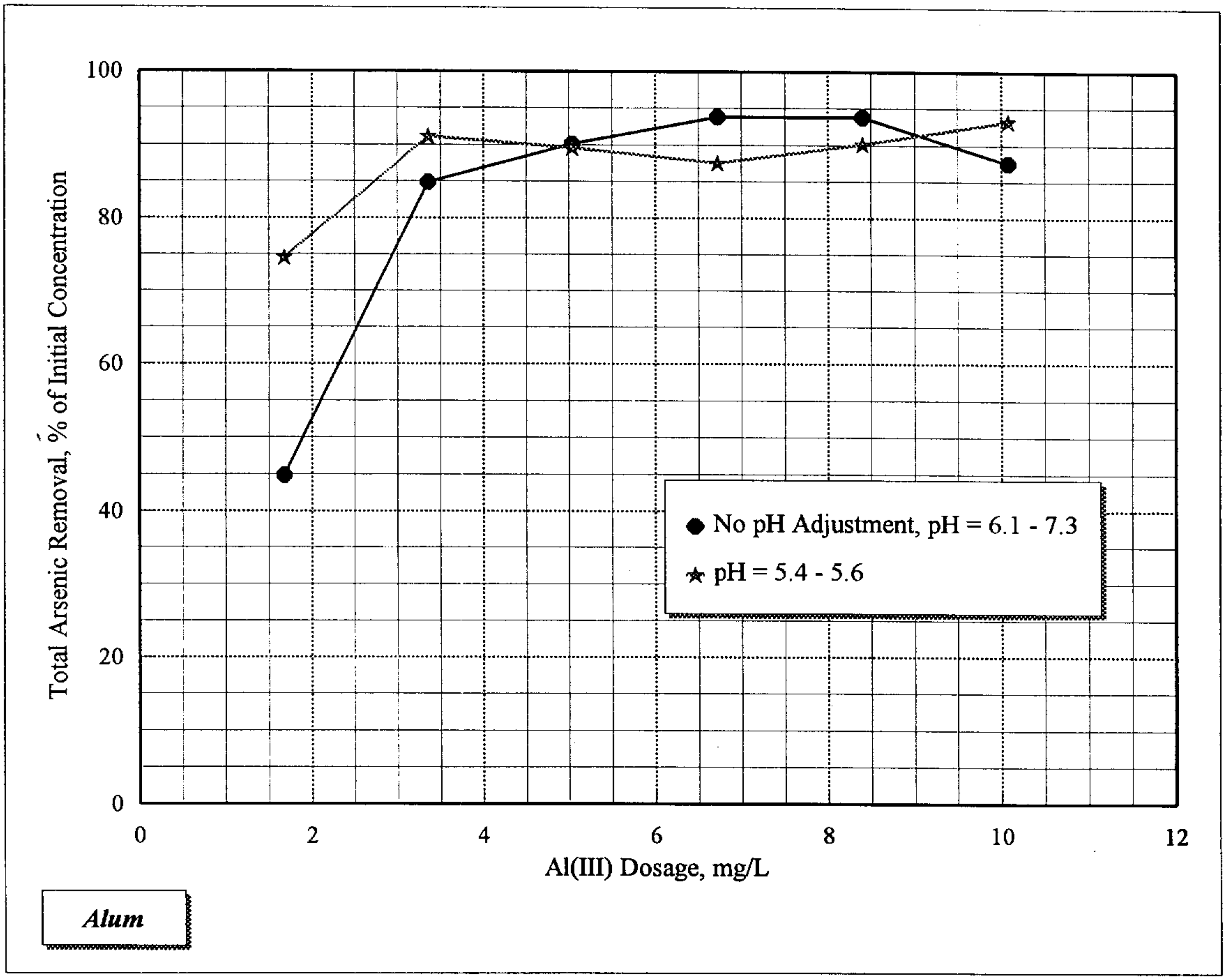

FIGURE 4-17

Experimental Results of Total Arsenic Removal with Alum

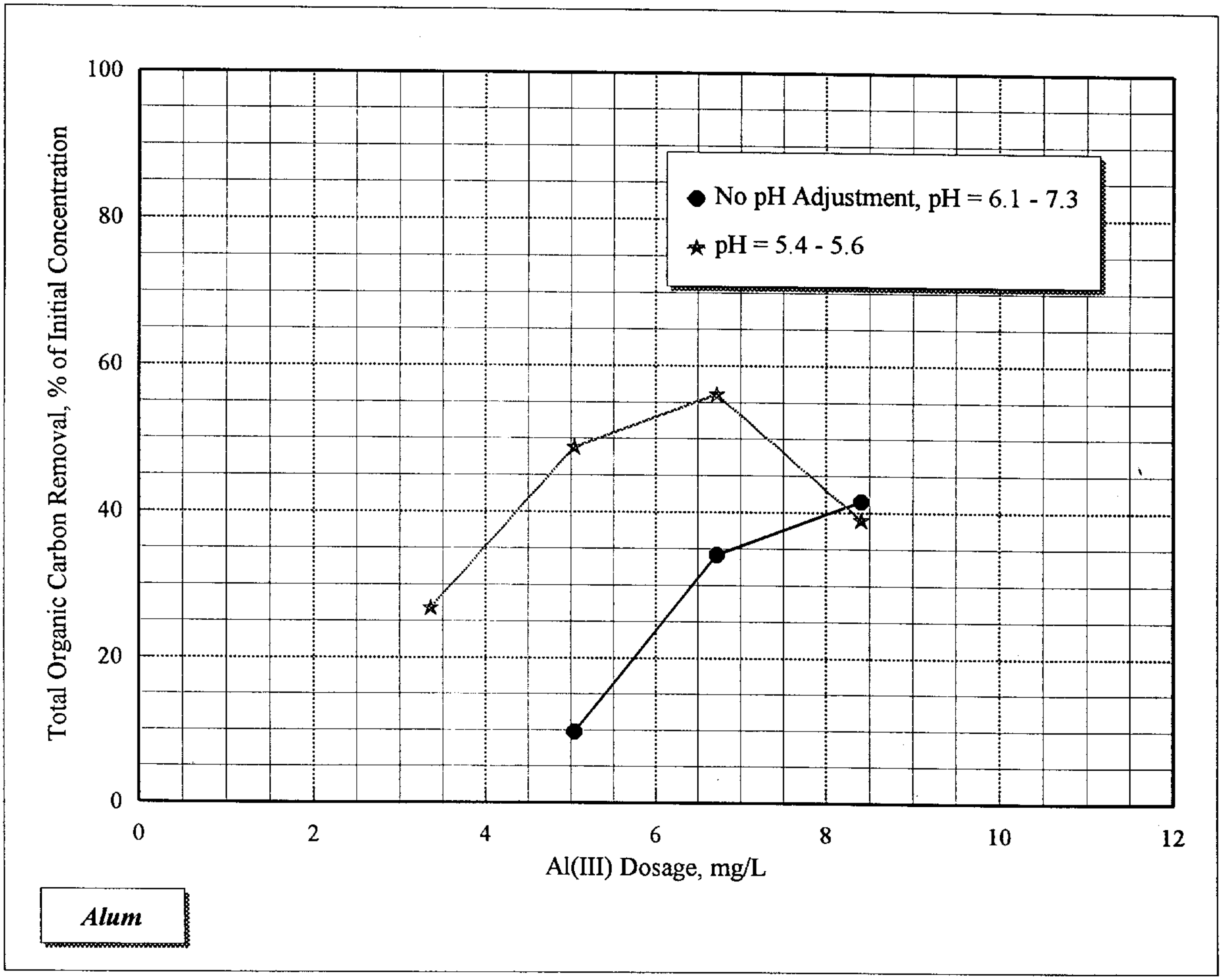

FIGURE 4-18

Experimental Results of TOC Organic Carbon Removal with Alum Coagulation

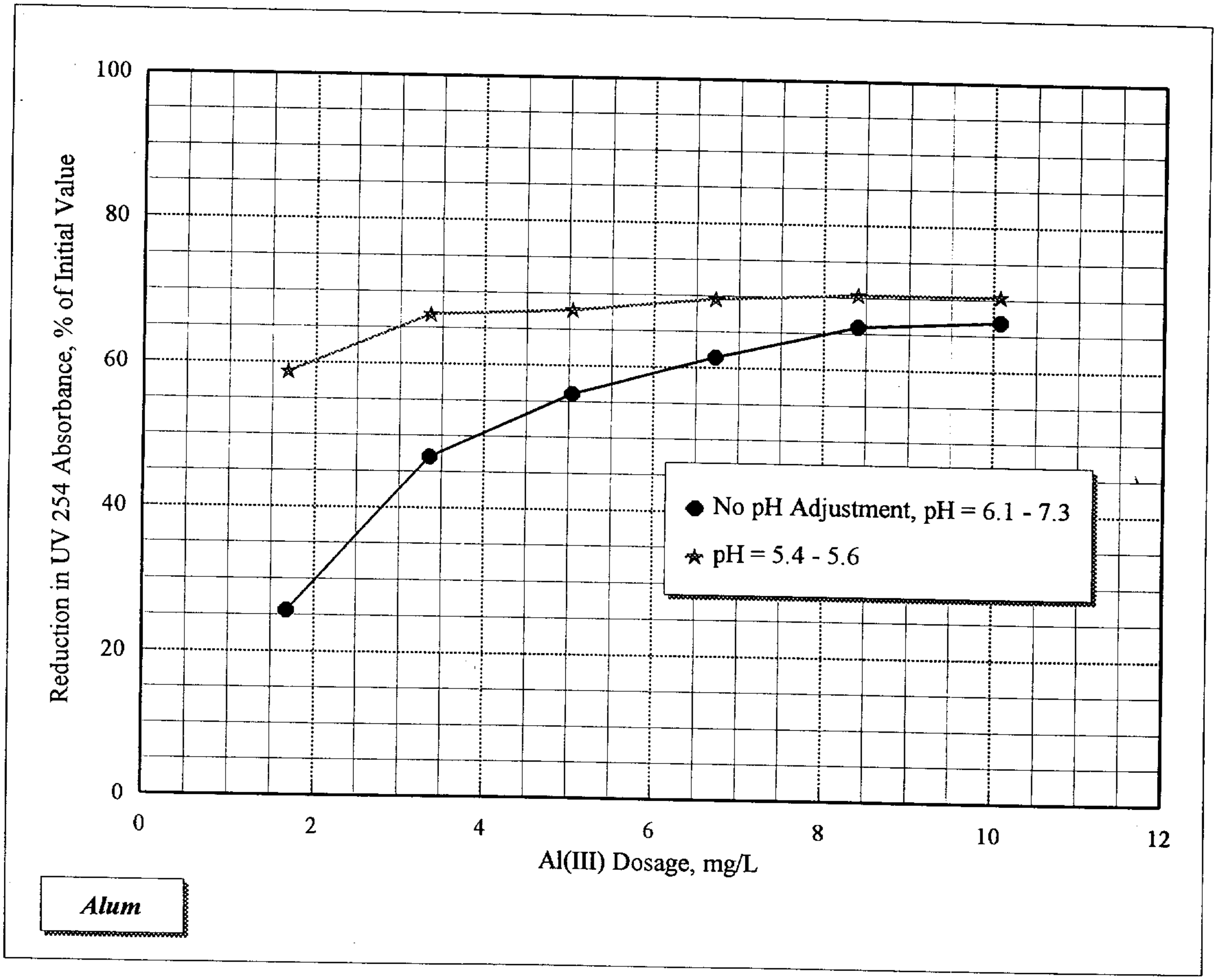

FIGURE 4-19

Experimental Results of Reduction in UV254 Absorbance with Alum Coagulation

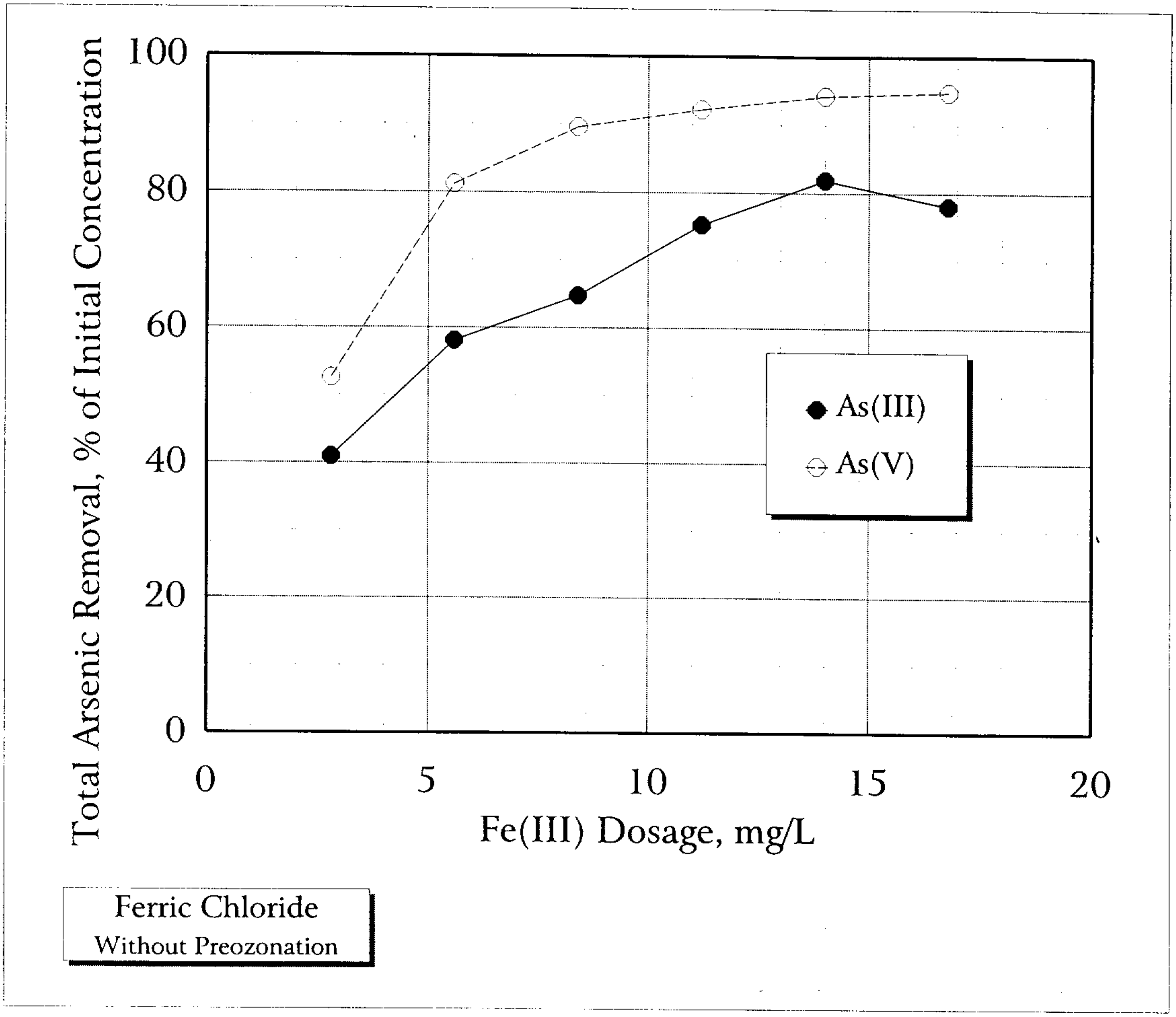

FIGURE 4-20

Comparison of As(III) and As(V) Removal Without Preozonation curves in Figure 4-20 clearly shows that although As(III) is removable by coagulation, its removal is much lower than that of As(V). To achieve high removal of As(III), conversion of As(III) to As(V) through some preoxidation process may be necessary.

Ferric sulfate coagulant was also investigated for As(III) removal in this study. The experimental results of As(III) removal with ferric sulfate and ferric chloride are compared in Figure 4-21. As(III) removal by both coagulants was identical at Fe(III) dosages lower than 8.4 mg/L. At Fe(III) dosages higher than 8.4 mg/L, the arsenic removal efficiencies for ferric chloride were higher by about 10 - 20 percent. This clearly shows that ferric sulfate is slightly less effective than ferric chloride for As(III) removal without preozonation.

REMOVAL OF As(III) WITH PREOZONATION

Clifford, et al. (1983), reported that the reaction rate for oxidation of As(III) to As(V) is slowed by dissolved oxygen in aqueous systems. A strong oxidant is needed if a high reaction rate is required. Ozone is one of the most powerful oxidants used in water treatment practice. The main reasons for using preozonation are (1) improvement in turbidity removal, (2) oxidation and fragmentation of taste- and odor-causing compounds that are removed effectively in biofilters, (3) improved disinfection, and (4) reduction of DBPs if followed by biofilters. A rapid growth in the application of ozonation in drinking water treatment practice has been noted across North America. In accordance with the information provided by the International Ozone Association (1995), the average annual growth was approximately 17 plants per year, or 491 mgd per year, in ozonation between 1991 and 1994. By May 1995, 106 potable water treatment plants with a total ozonation capacity of 2,665 mgd were in operation in the U. S. At that time, 21 plants with a total ozonation capacity of 459.3 mgd were under construction. The potential benefit of using ozonation as a pretreatment to enhance As(III) removal is therefore very clear, because oxidation of As(III) to As(V) will be achieved in these facilities.

In this study, arsenic-spiked raw water samples were preozonated in the ozone contact chamber of the pilot plant at the RHWTP. The ozone application rate was about 9 mg/L*. Four preozonated water samples were collected. Three samples were freshly spiked with As(III) and one with As(V) prior to preozonation. The initial total arsenic concentration in As(III)-spiked samples was within the range of 13.2 - 14.2 μg/L. Two of these three samples were coagulated with ferric chloride, and was coagulated with ferric sulfate. The As(V)-spiked sample had an initial total arsenic concentration of 20.9 μg/L and was coagulated with ferric chloride. No pH adjustment was considered in any of these four jar tests.

Experiments with ferric chloride showed that the removal efficiencies of As(III) were significantly improved after preozonation. As(III) removals with and without preozonation are compared in Figure 4-22. Removal efficiencies of around 90 percent were achieved at Fe(III) dosages higher than 8.4 mg/L. After preozonation, the results of total arsenic removal for As(III) are similar to that for As(V). These results, shown in Figure 4-23, clearly imply that complete oxidation of As(III) to As(V) was achieved in the preozonation process.

The results of As(V) removal with and without preozonation are shown in Figure 4-24. The As(V) removal with preozonation is significantly higher than that without preozonation at a low coagulant dosage [2.8 mg/L as Fe(III)]. Higher removal of As(III) may be the result of slightly improved turbidity removal after preozonation at low dosages. The experimental results of turbidity removal with and without preozonation are compared in Figure 4-25. Another study has also shown that improved turbidity removal is achieved after preozonation (Qasim and Hossain 1992).

The effect of preozonation with ferric sulfate on the removal of As(III) and turbidity was also investigated. A comparison of As(III) removal data with ferric sulfate and ferric chloride after preozonation is shown in Figure 4-26. Within the range of Fe(III) dosages below 8.4 mg/L, total arsenic removal is much lower with ferric sulfate than with ferric chloride. At Fe(III) dosages higher than 10.5 mg/L, the total arsenic removal by both coagulants is equal. Figure 4-27 shows

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* The water depth in the ozone contact chamber (without baffle) at the pilot plant is 4'6". An ozone transfer efficiency of less than 30 percent is expected.

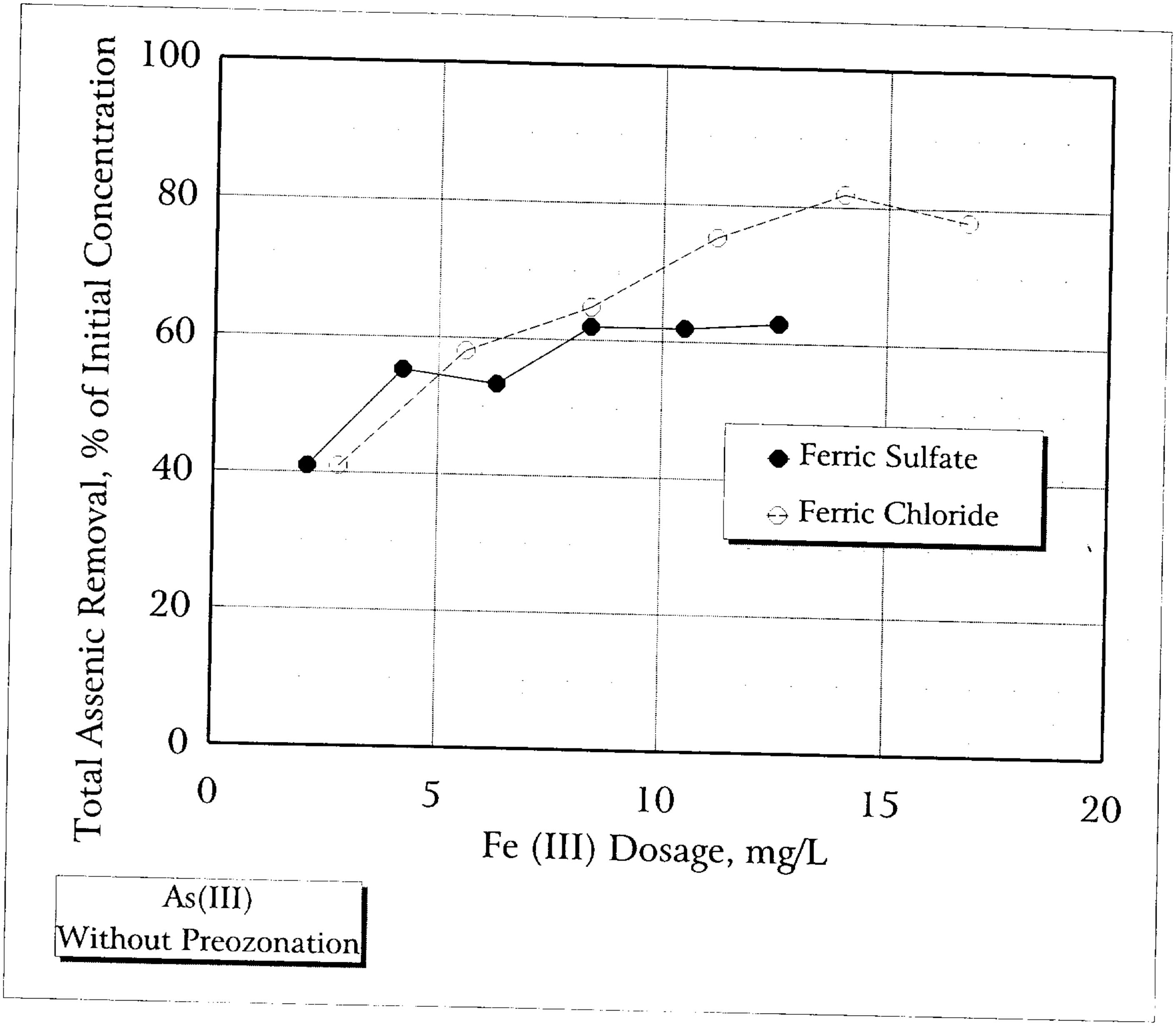

FIGURE 4-21

Comparison of As(III) Removal Without Preozonation
with Ferric Sulfate and Ferric Chloride

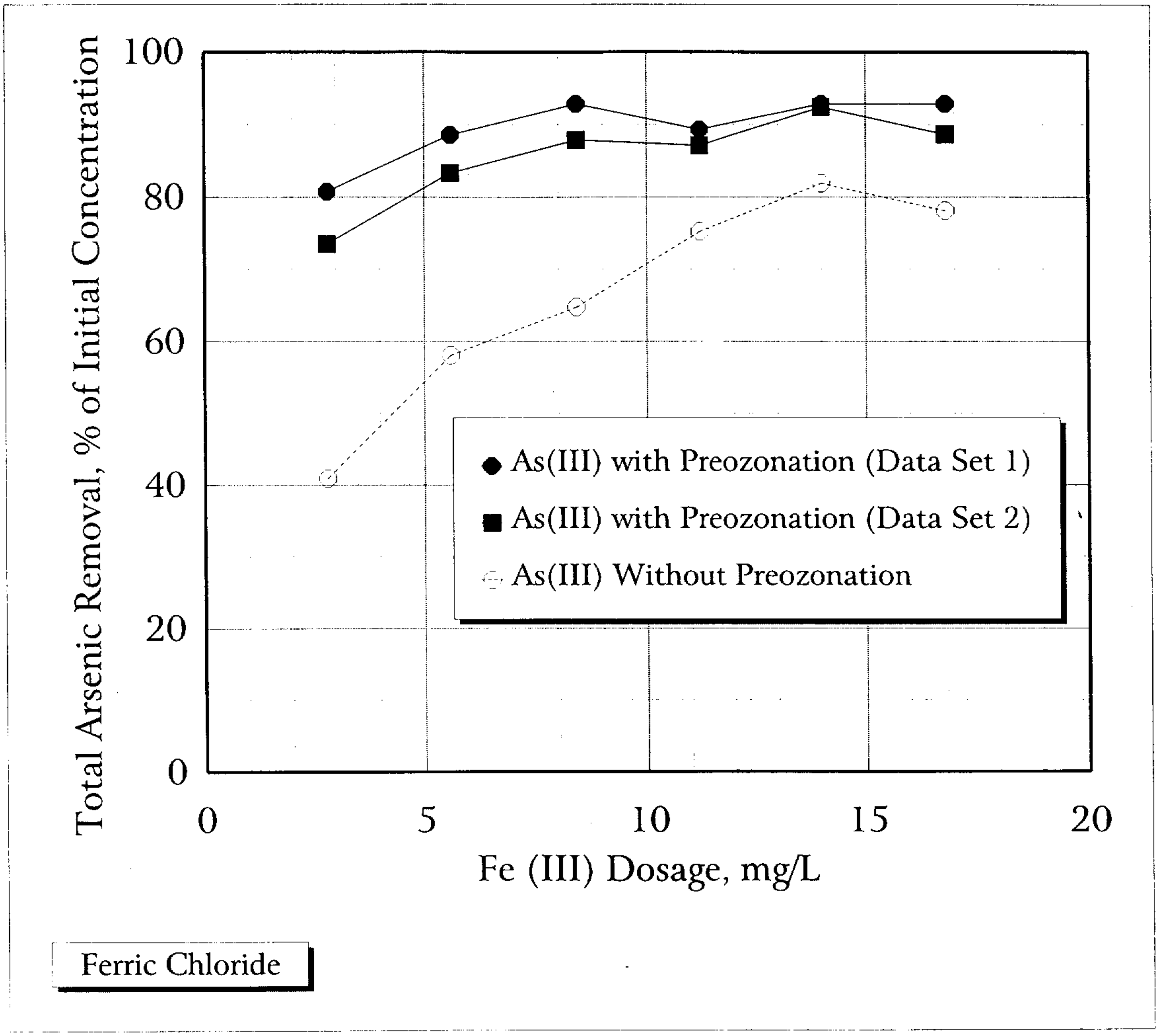

FIGURE 4-22

Comparison of As(III) Removal with and Without Preozonation

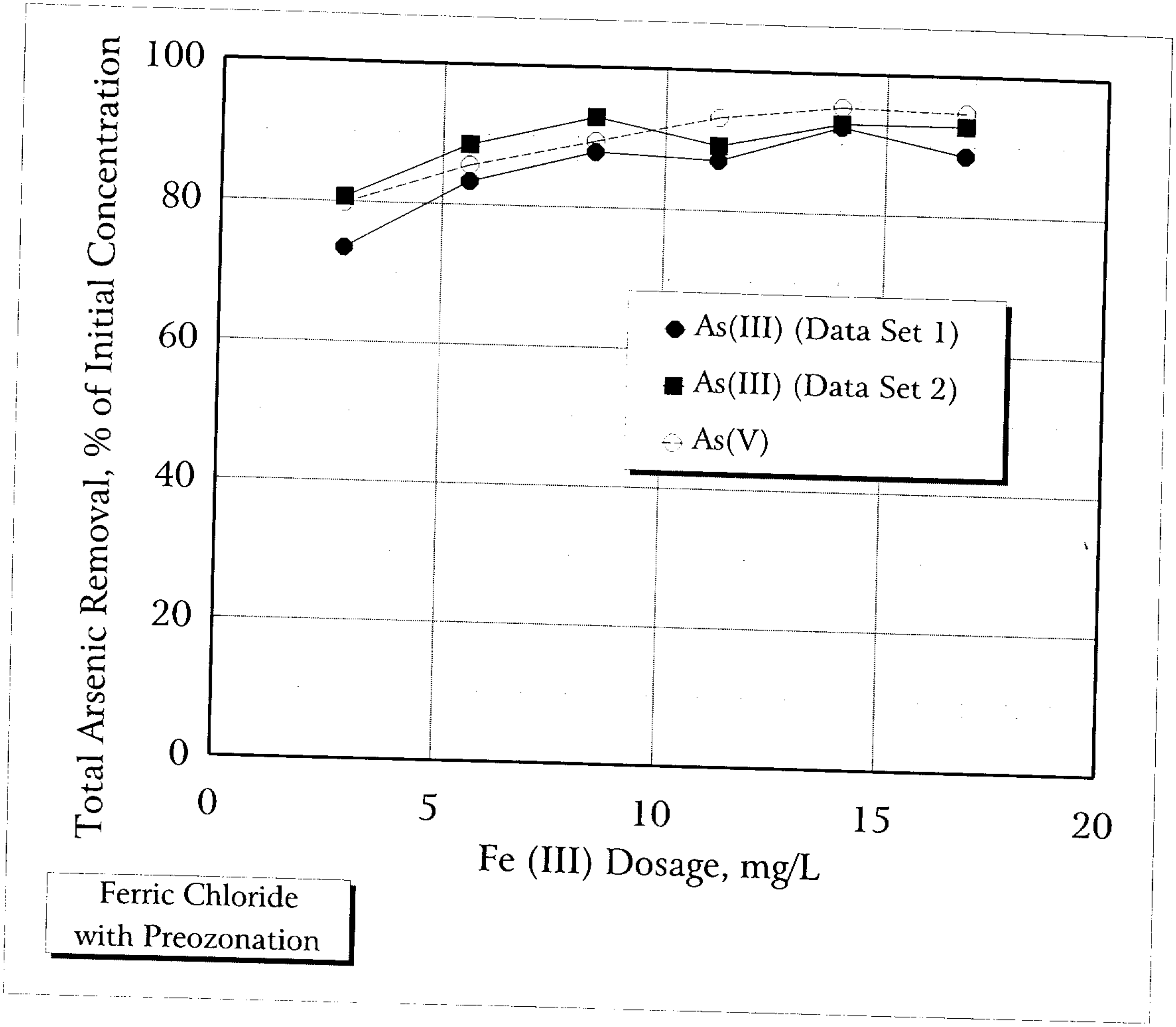

FIGURE 4-23

Comparison of As(III) and As(V) Removal with Preozonation

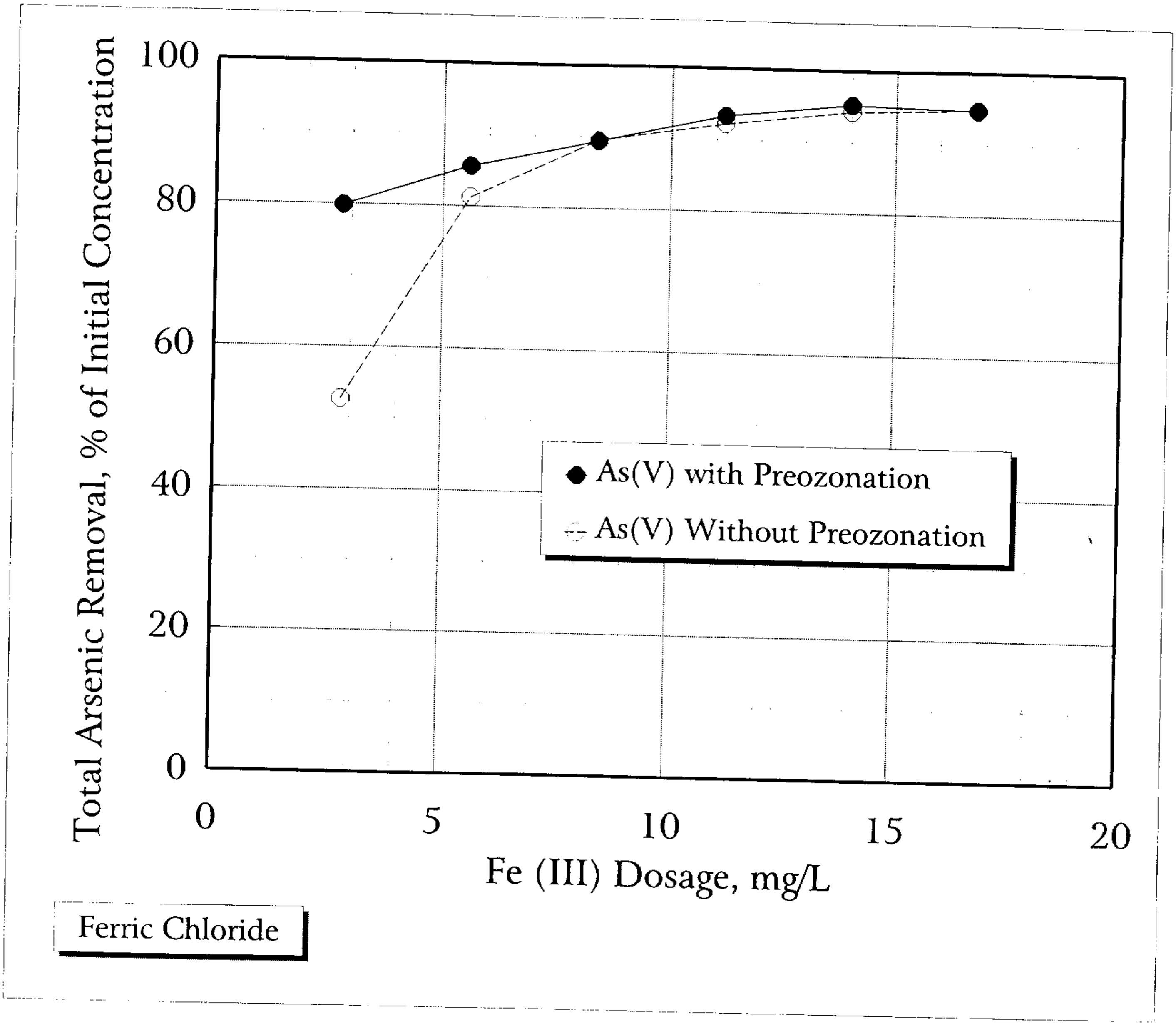

FIGURE 4-24

Comparison of As(V) Removal with and Without Preozonation

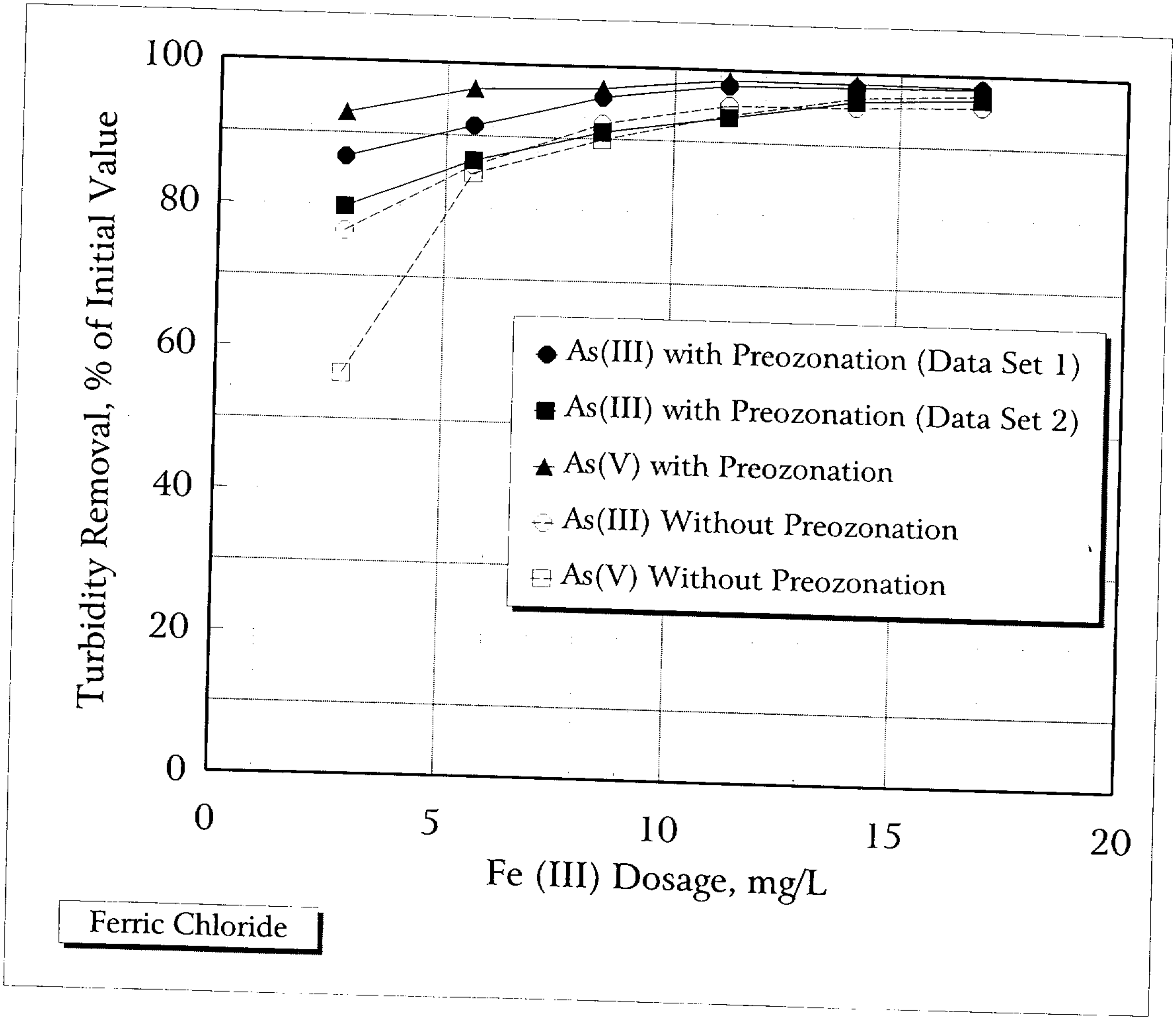

FIGURE 4-25

Comparison of Turbidity Removal with and Without Preozonation

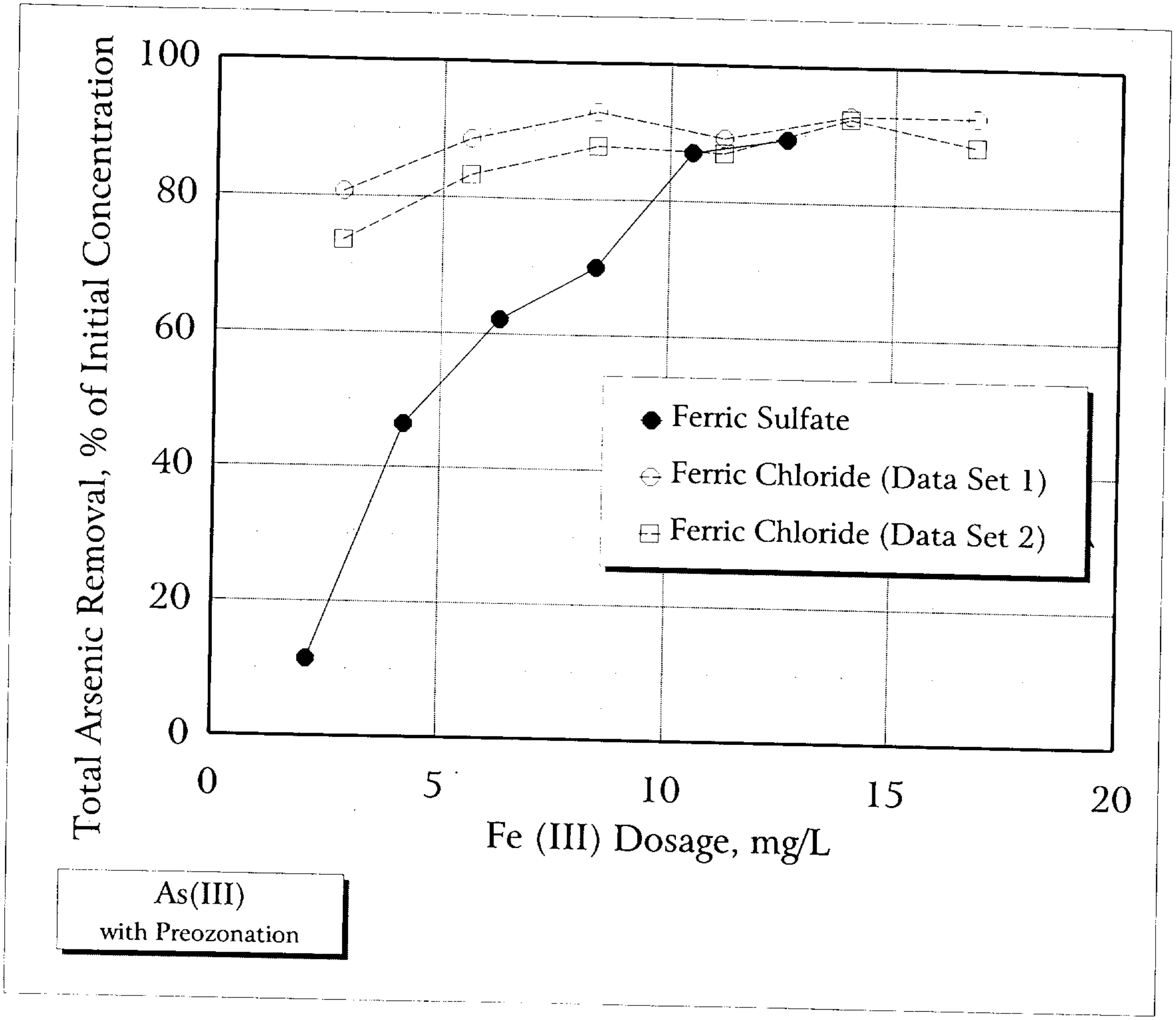

FIGURE 4-26

Comparison of As(III) Removal with Preozonation by Use of Ferric Sulfate and Ferric Chloride

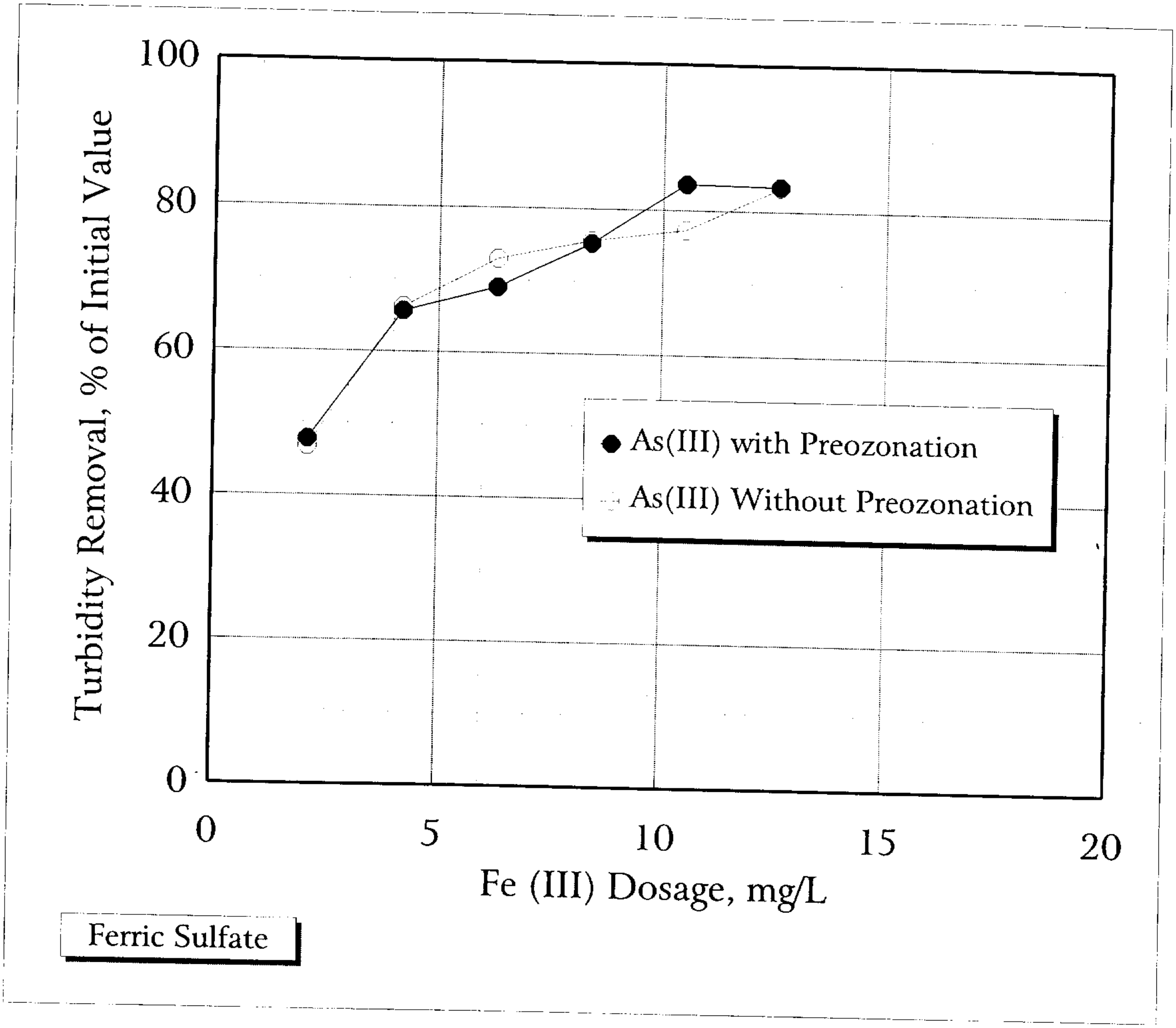

FIGURE 4-27

Comparison of Turbidity Removal by Use of
Ferric Sulfate Coagulation with and Without Preozonation

the results of turbidity removal with ferric sulfate coagulation with and without preozonation. There is clearly no improvement in turbidity removal by preozonation. Poor total arsenic removal with ferric sulfate is obviously due to the lack of improvement in turbidity by preozonation. It is therefore clear that ferric sulfate coagulation after preozonation is less effective for removal of both As(III) and turbidity than ferric chloride coagulation.

4.3.3 SLUDGE PRODUCTION

The quantities and properties of sludge are important parameters for developing effective residuals management options at water treatment plants. The principal sources of sludge at municipal water treatment plants depend upon the processes utilized. In this study, the characteristics of sludge produced by enhanced coagulation were investigated. The main purpose of this investigation was to (1) determine the mass and volume of sludge produced at different coagulant dosages and (2) estimate the accumulation of arsenic in the sludge. These efforts will provide information for developing sludge disposal options under current sludge disposal guidelines. The experimental results are presented and discussed below.

QUANTITIES OF SLUDGE

Coagulation sludge basically consists of the natural turbidity-causing materials in raw lake waters, and the amorphous ferric hydroxide formed by adding coagulant. The sludge production rate and its properties are influenced by (1) the raw water properties, (2) the type of coagulant, and (3) coagulation conditions such as coagulant dosage and pH. In this study, a batch of raw water samples was collected and stored for the entire investigation. Thus, the effect of changes in raw water quality on sludge production was eliminated. The average initial TSS and turbidity in the stored samples were 8.79 mg/L and 5.37 NTU, respectively. Jar tests were conducted with ferric chloride and ferric sulfate. In general, the coagulants showed similar sludge production trends. On the other hand, the data for ferric sulfate were not complete and had some inconsistencies. Therefore, only the results of ferric chloride coagulation are presented and discussed here. The experimental variables were the coagulant dosage and pH. The Fe(III) dosages of 2.8, 5.6, 11.2, and 16.8 mg/L were used in the jar tests with ferric chloride. The pH adjustment was made by adding sulfuric acid.

Coagulation sludge is formed during the coagulation and flocculation processes. Usually, a major percentage of sludge removal is achieved in the sedimentation basin. A small portion of the residual solids is captured in the filters and eventually recovered by the filter backwash system. Therefore, the total sludge quantity contains settled sludge after sedimentation and recovered solids from the filter backwash system. In this study, the sludge quantities from these two facilities were determined by assuming that (1) sludge from the sedimentation basin was equal to the sludge settled in the standard jar tests and (2) sludge from the filter backwash system was equal to the amount of TSS remaining in the settled water after settling. This also implies that the filter backwash recovery system captured 100 percent of TSS in the settled water.

The sludge quantity is usually reported on the basis of both mass and volume. In this study, the quantity of sludge from the sedimentation basin is presented on both a mass and volume basis. The sludge from the filter backwash system is expressed on only mass basis.

Sludge Mass

In the coagulation process, the total mass of sludge generally increases with an increased coagulant dosage. It was found that the effect of pH on the total mass of sludge produced is small. Therefore, the total mass of sludge produced was determined from the experimental data without pH adjustment. These results are shown in Figure 4-28. A linear relationship between the total amount of sludge mass produced and the amount of Fe(III) applied is clearly noted. The linear regression line is expressed by Eq. (4-1):

$$[\text{Sludge}]_{\text{mass}} = 9.58 + 1.69 \times [\text{Dosage}]_{\text{Fe(III)}} \qquad (4 - 1)$$

where $[\text{Sludge}]_{\text{mass}}$ = total amount of sludge mass produced (mg-TSS/L raw water treated);

$[\text{Dosage}]_{\text{Fe(III)}}$ = coagulant dosage applied [mg/L as Fe(III)].

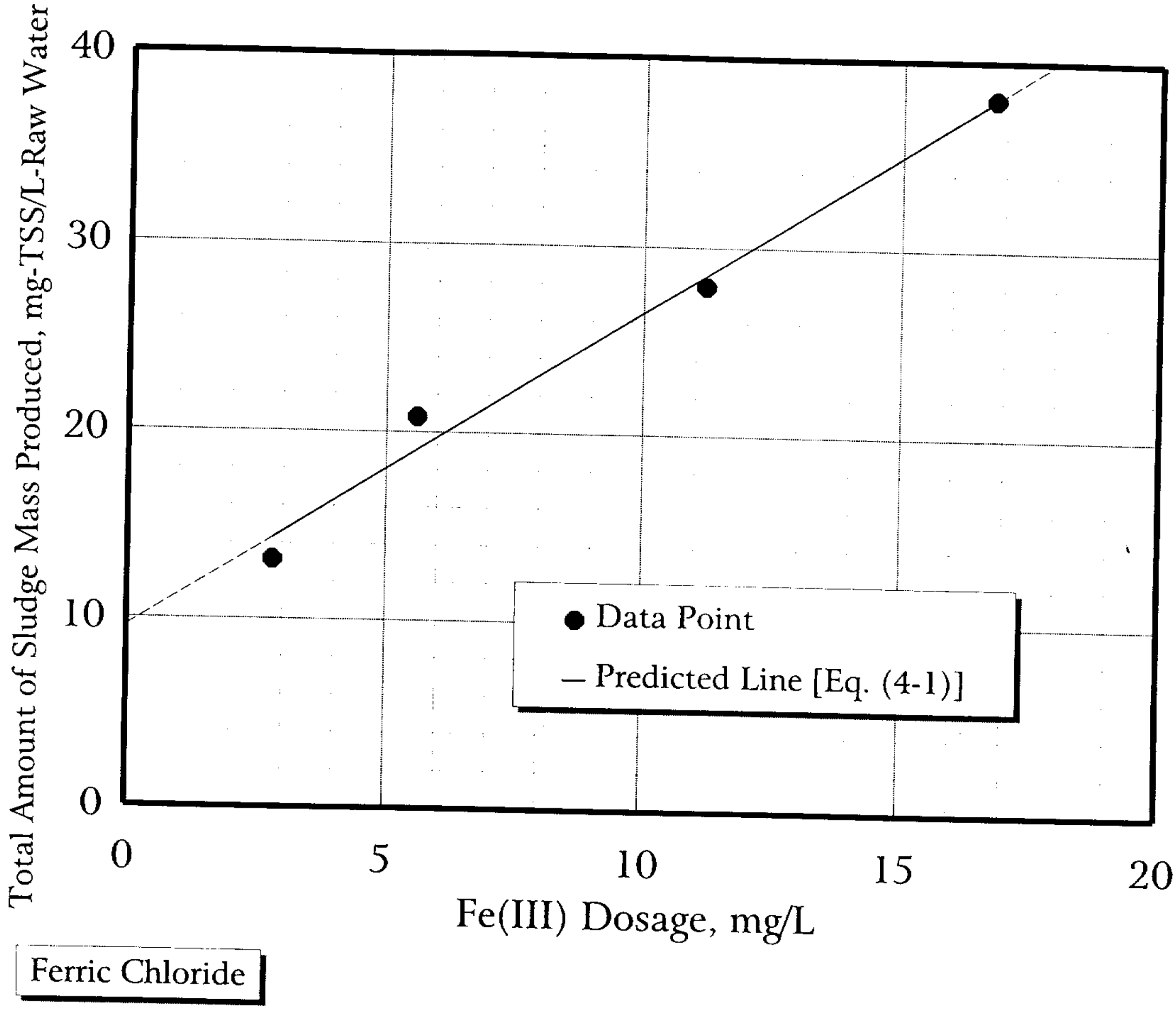

FIGURE 4-28

Relationship Between Total Amount of Sludge Mass Produced
and Coagulant Dosage Applied

The intercept on the Y-axis gives a sludge quantity of 9.58 mg/L. This value is close to the TSS value of 8.79 mg/L in the raw water sample. Therefore, Eq. (4-1) can also be expressed as a function of the coagulant dosage and the initial TSS in the raw water. The modified relationship is expressed by Eq. (4-2):

$$[\text{Sludge}]_{\text{mass}} = [\text{TSS}]_{\text{initial}} + 1.69 \times [\text{Dosage}]_{\text{Fe(III)}} \qquad (4 - 2)$$

where $[\text{TSS}]_{\text{initial}}$ = initial total suspended solids in the raw water (mg/L).

The slope of the line expressed by Eq. (4-1) gives a value of 1.69 mg-TSS/mg-Fe(III). This slope represents the sludge mass contributed by the precipitation of amorphous ferric hydroxide. The stoichiometrical value for ferric hydroxide precipitation is 1.91 mg-$Fe(OH)_3$/mg-Fe(III). Others have reported that sludge production by iron precipitation is in the range of 1.5 - 2 mg of sludge per mg of iron in the water (ASCE and AWWA 1990). The value obtained in this study is close to that of the chiometrical value and is within the typical range.

The quantity of sludge produced by settling and that recovered from filter backwashing are shown separately in Figure 4-29. The results clearly show that at a higher coagulant dosage, a major portion of sludge is removed in the sedimentation basin. Therefore, the solids loading on the filter is significantly reduced, resulting in longer filter runs.

Sludge Volume

A relationship between the volume of sludge produced by settling in an Imhoff cone and the coagulant dosage was developed from the experimental data. This relationship is shown in Figure 4-30 and is expressed by Eq. (4-3):

$$[\text{Sludge}]_{\text{volume}} = -3.31 + 5.92 \times \text{Ln}\,[\text{Dosage}]_{\text{Fe(III)}} \qquad (4 - 3)$$

where $[\text{Total Sludge}]_{\text{volume}}$ = total amount of sludge volume occupied (mL-sludge/L raw water).

It may be noted that the positive intercept on the X-axis corresponds to an Fe(III) dosage of 1.75 mg/L. This is the minimum dosage of Fe(III) necessary to produce a measurable volume of sludge.

The results also clearly show that the volume of coagulation sludge increases with increased coagulant dosage. The relationship, however, is nonlinear. The slope of the curve decreases with coagulant dosage, indicating less volume occupied. It is also noted that (1) the sludge mass shows a constant sludge production rate (Figure 4-28) and (2) the major portion of sludge (> 85 percent) is settled in the sedimentation basin (Figure 4-29). The solids concentration in the settled sludge is shown in Figure 4-31. There is a significant decrease of mass concentration in the sludge with an increase of the Fe(III) dosage to 4 mg/L. A minimum mass concentration of 2.5 g/L is reached at an Fe(III) dosage of 8 mg/L. There is, however, a slight increase in mass concentration with an increase of the Fe(III) dosage beyond 8 mg/L.

ARSENIC ACCUMULATION IN SLUDGE

The removal of arsenic from raw water by enhanced coagulation is achieved by immobilization of the soluble arsenic in the coagulant sludge. As arsenic is removed from the water, its concentration will increase in the sludge. The final concentration of arsenic in the sludge may eventually govern the ultimate sludge disposal or reuse options. Therefore, a great deal of effort has been devoted to developing a generalized equation for estimating the concentration of arsenic in sludge with different initial arsenic concentrations and coagulant dosages.

It has been clearly demonstrated in this study that the production of sludge mass is dependent upon the coagulant dosage and initial TSS in raw water. Equation (4-2) was developed to estimate the coagulant dosages and sludge quantities at different initial TSS concentrations in raw water.

The removal of arsenic from raw water is primarily dependent upon the initial arsenic concentration and the coagulant dosage applied. The removal process, however, is a complex combination of several mechanisms. In general, the adsorption and/or coprecipitation of arsenic species onto the amorphous ferric hydroxides and coagulation of these arsenic-carrying amorphous

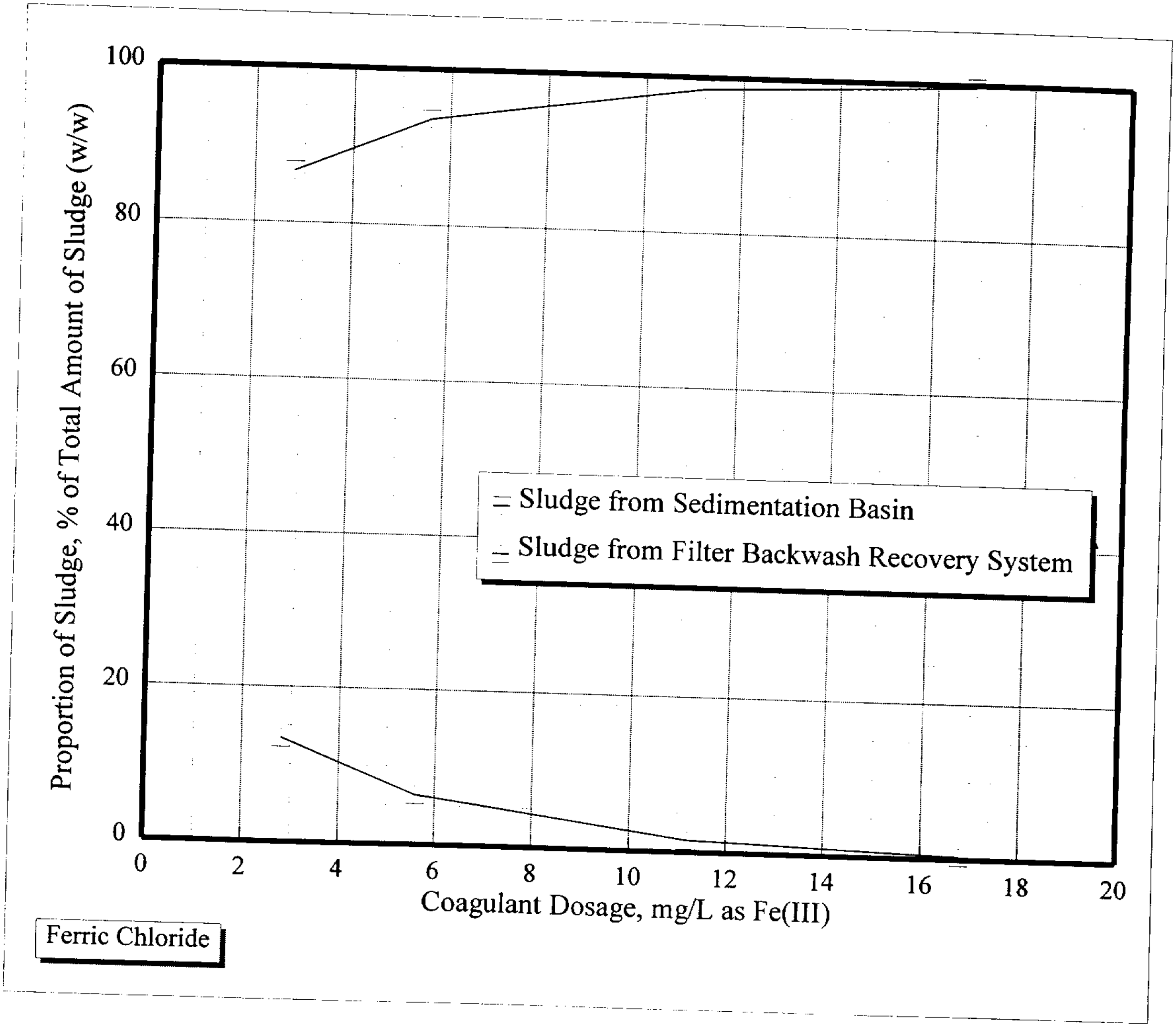

FIGURE 4-29

Proportion of Sludge from Sedimentation Basin and Filter Backwash Recovery System

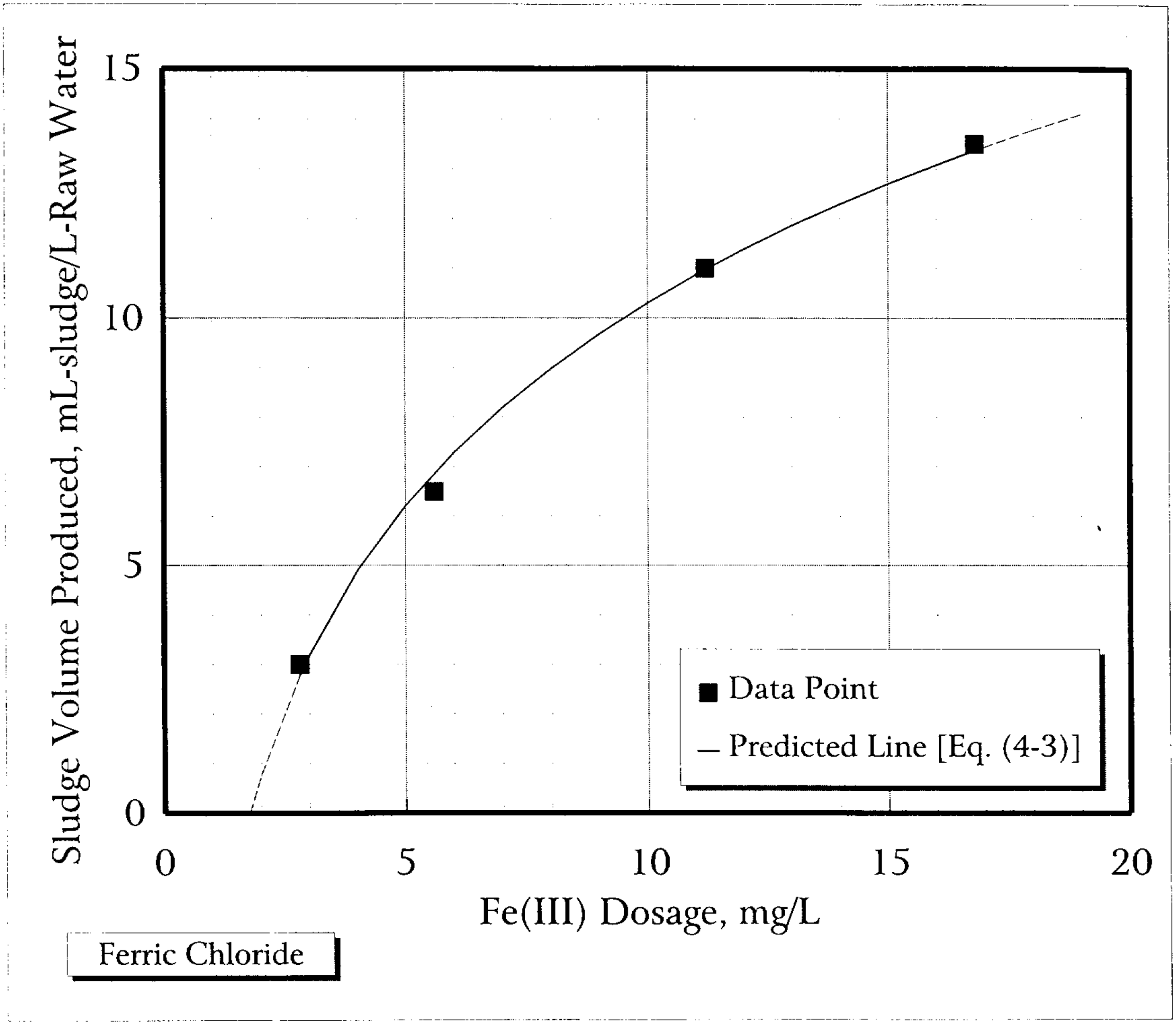

FIGURE 4-30

Relationship Between Sludge Volume and Coagulant Dosage Applied

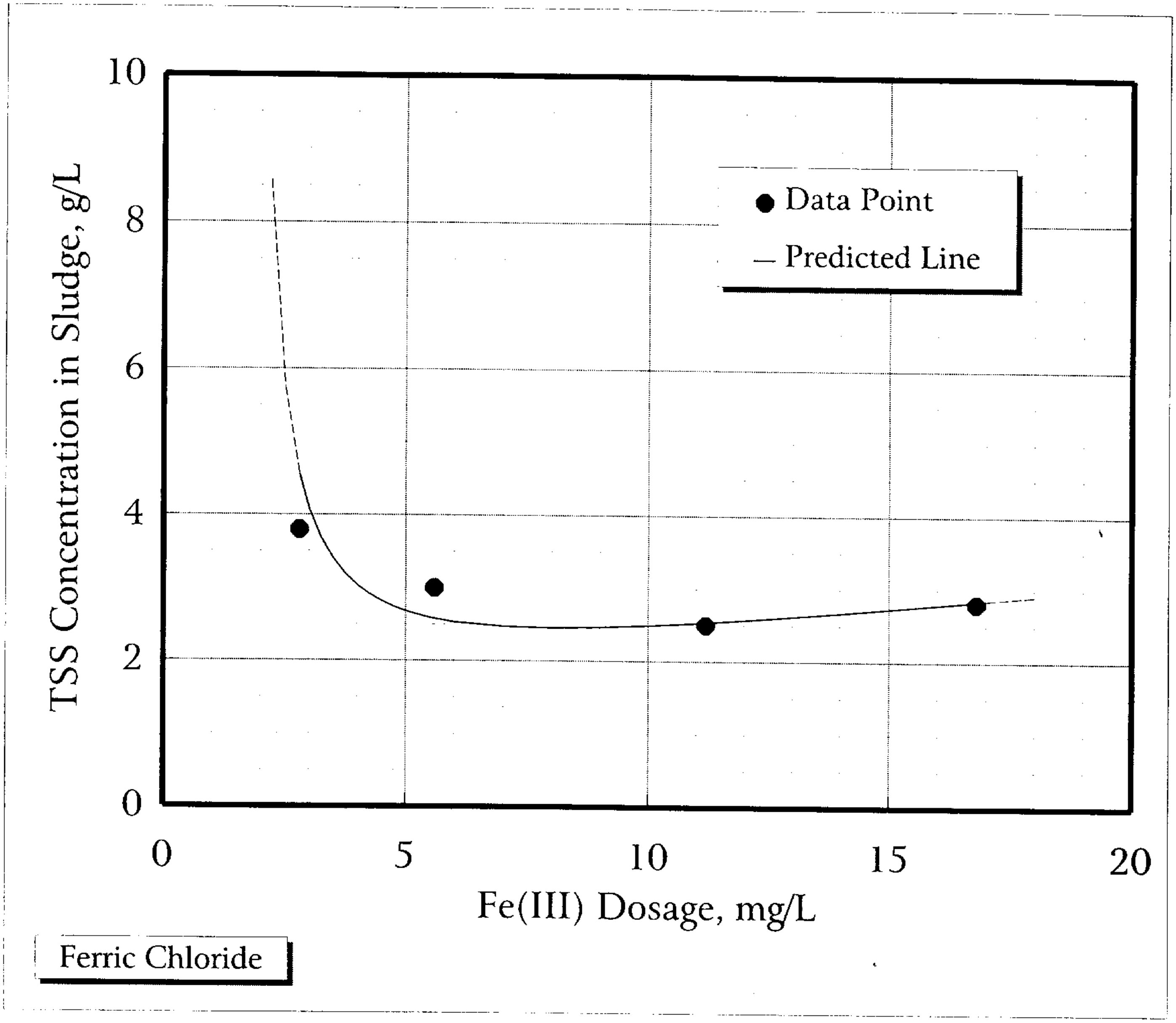

FIGURE 4-31

TSS Concentration in Sludge

ferric hydroxides can influence the removal rate. Because of this complexity, this topic has been presented in a later section of this report. A generalized equation, however, has been developed to give a maximum achievable overall arsenic removal as a function of initial and equilibrium concentrations of arsenic and the Fe(III) dosage applied in the coagulation process. This relationship is expressed by Eq. (4-9) and is presented in Section 4.3.4. By combining the sludge production [Eq. (4-2)] and arsenic removal [Eq. (4-9)], a generalized equation has been obtained for estimating the arsenic concentration in the sludge. This relationship is expressed by Eq. (4-4):

$$[\text{Arsenic}]_{\text{sludge}} = \frac{(-5.45 + 8.21 \times [\text{Arsenic}]_{\text{initial}}) \times [\text{Dosage}]_{\text{Fe(III)}}}{(1 + 8.21 \times [\text{Dosage}]_{\text{Fe(III)}}) \times ([\text{TSS}]_{\text{initial}} + 1.69 \times [\text{Dosage}]_{\text{Fe(III)}})} \quad (4 - 4)$$

where $[\text{Arsenic}]_{\text{sludge}}$ = arsenic accumulation in the sludge (g-As/kg-sludge);

$[\text{Arsenic}]_{\text{initial}}$ = initial total arsenic concentration (μg/L).

The concentration of arsenic in sludge is estimated from Eq. (4-4) for five initial total arsenic concentrations in raw water: 5, 10, 20, 30, and 50 μg/L. The initial TSS in raw water is assumed to be 10 mg/L. The final plots of arsenic concentration in sludge for these conditions at different Fe(III) dosages are shown in Figure 4-32. These plots show a peak in arsenic concentration in the sludge at an Fe(III) dosage of 0.8 - 0.9 mg/L followed by a gradual decline. The following explanations apply to the arsenic concentration profile in the sludge:

(1) The arsenic concentration in the sludge increases with an increase in the initial concentration of arsenic in the raw water.

(2) At a very low Fe(III) dosage (less than 0.8 mg/L), the arsenic concentration in the sludge increases until it reaches a peak value. The reason for this increase in arsenic concentration in the sludge is due to a high arsenic removal rate and low quantities of sludge produced at these low coagulant dosages.

(3) At Fe(III) dosages greater than 1.0 mg/L, the sludge mass quantity is constantly increased while the amount of arsenic removed is increased more and more slowly with the increase in the Fe(III) dosage. As a result, the overall concentration of arsenic in the sludge decreases gradually.

From the results and discussion provided above, it can be generalized that the arsenic concentration in sludge using the enhanced coagulation process will be significantly less than that obtained by conventional coagulation.

4.3.4 ARSENIC REMOVAL MECHANISM

The removal of arsenic from drinking water by the enhanced coagulation process is completed in two major steps. Step 1 is an immobilization process in which soluble arsenic is converted into particulate arsenic. In this step, arsenic species are attached onto the surface of amorphous ferric hydroxide precipitates by an adsorption mechanism and/or embedded into the arsenic-iron complexes by a coprecipitation mechanism. The driving forces corresponding to these interactions may be the simple electrostatic attraction between oppositely charged arsenic species and the surface of amorphous ferric hydroxide precipitates, and/or the formation of special chemical bonds between arsenic species and some functional groups on the surface of iron oxides. Step 2 is a process in which the particulate arsenic is separated from the aqueous system. The separation of these arsenic-carrying particles is dependent upon the mechanisms such as destabilization, aggregation, transportation of colloidal-size particles, and sedimentation of these flocculated solids.

In accordance with the mechanisms involved in the two steps, overall arsenic removal by enhanced coagulation can be expressed as a product of the arsenic immobility in Step 1 and the removal efficiency of arsenic-carrying particles in Step 2. This expression is given by Eq. (4-5):

$$E_{\text{overall}} = E_1 \times P_2 \qquad (4-5)$$

where E_{overall} = overall arsenic removal (ug-As/L raw water treated);
E_1 = arsenic immobility in step 1 (ug-As/L raw water treated); and
P_2 = removal efficiency of arsenic carrying particle (%).

In Eq. (4-5), E_1 is determined by adsorption and/or coprecipitation mechanisms and is independent of the particle separation process. The best parameter to describe the immobility of arsenic is the removal of dissolved arsenic from water. For a perfect removal of arsenic-carrying particles (P_2 =

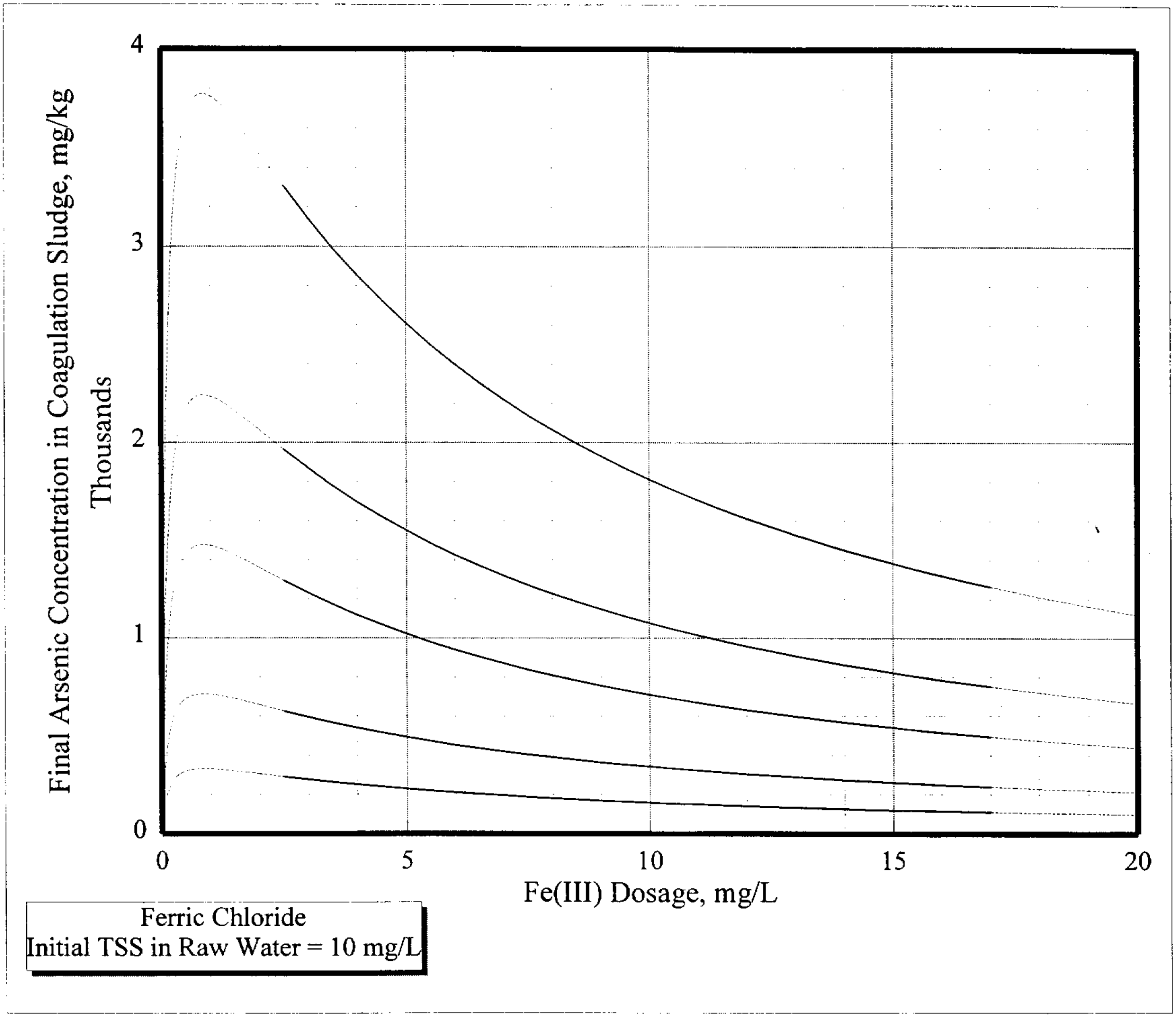

FIGURE 4-32

Arsenic Accumulation in Sludge

100%), the overall arsenic removal reaches the maximum achievable value that is equal to the removal of dissolved arsenic ($E_{overall} = E_1$). When ideal conditions cannot be provided ($P_2 < 100\%$), the overall arsenic removal is less than the removal of dissolved arsenic, $E_{overall} < E_1$. Under such conditions, the overall arsenic removal is usually described by the removal of total arsenic from the water. The difference between dissolved and total arsenic removal, therefore, is the arsenic concentration that is retained as particulate forms in the water. The parameter P_2 is determined by the same mechanisms that influence turbidity removal and is independent of the mechanisms involved in Step 1. The efficiency of turbidity removal, therefore, may be directly applicable to P_2 and then further connected to the overall arsenic removal that is expressed by Eq. (4-5).

In this study, both dissolved and total arsenic removals were investigated by using arsenic-spiked tap water samples. The experimental results are presented and discussed below. The effects of initial arsenic concentration and turbidity removal on arsenic removal will be discussed later.

DISSOLVED ARSENIC REMOVAL

The removal of dissolved arsenic is controlled by adsorption and/or coprecipitation mechanisms. These mechanisms are generally described by adsorption equations. The Langmuir isotherm is the most popular equation used to express adsorption phenomena. In this equation, the amount of adsorbate adsorbed onto the adsorbent applied is a function of adsorbate concentration under equilibrium conditions. In this study, the adsorbate is dissolved arsenic, and the adsorbent is ferric hydroxide. The relationship between the amount of dissolved arsenic removed per unit mass of ferric ions applied and the corresponding dissolved arsenic concentration remaining was developed. Experimental data are shown in Figure 4-33. Since the dissolved arsenic concentration remaining in settled water is small and falls within a narrow range between 1 and 6 μg/L, the Langmuir expression needs to be modified to fit the experimental data; a linear relationship is obtained. This simplified Langmuir equation is expressed by Eq. (4-6):

$$[\text{Arsenic}]_{\text{dissolved, removed}} = -5.45 + 8.21 \times [\text{Arsenic}]_{\text{dissolved, remaining}} \qquad (4 - 6)$$

where $[\text{Arsenic}]_{\text{dissolved, removed}}$ = amount of dissolved arsenic removed per unit mass of ferric ion applied [μg-As/mg-Fe(III)]

$[\text{Arsenic}]_{\text{dissolved, remaining}}$ = dissolved arsenic concentration remaining (μg/L).

It is clearly noted in Figure 4-33 that the positive intercept on the horizontal axis gives a dissolved arsenic concentration of about 0.7 μg/L. Theoretically, this line must pass through the origin. The intercept value in Figure 4-33, and therefore may be related to the detection limit of soluble arsenic, which is 1 μg/L*. Any value below the detection limit was plotted as 1 μg/L. The slope of the line [Eq. (4-6)] is 8.21 μg-As/mg-Fe(III) per μg-As/L remaining and represents the capacity of ferric hydroxide to adsorb the dissolved arsenic from water.

Total Arsenic Removal

The removal of total arsenic is dependent upon both the initial adsorption of dissolved arsenic and the following separation of arsenic-carrying particles. The mechanism of total arsenic removal, therefore, becomes much more complex than that of adsorption. To simplify the analysis, the removal of total arsenic is expressed by an empirical equation. A linear relationship between total arsenic removal and total arsenic remaining has been observed in this study. This relationship is expressed by Eq. (4-7) and is shown in Figure 4-34.

$$[\text{Arsenic}]_{\text{total, removed}} = -0.460 + 2.40 \times [\text{Arsenic}]_{\text{total, remaining}} \qquad (4 - 7)$$

where $[\text{Arsenic}]_{\text{total, removed}}$ = amount of total arsenic removed per unit mass of ferric ion applied (μg-As/mg-Fe(III))

$[\text{Arsenic}]_{\text{total, remaining}}$ = total arsenic concentration remaining (μg/L).

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*Centrifuged water samples were analyzed for total arsenic. It is assumed that total arsenic in centrifuged samples is equal to the dissolved arsenic.

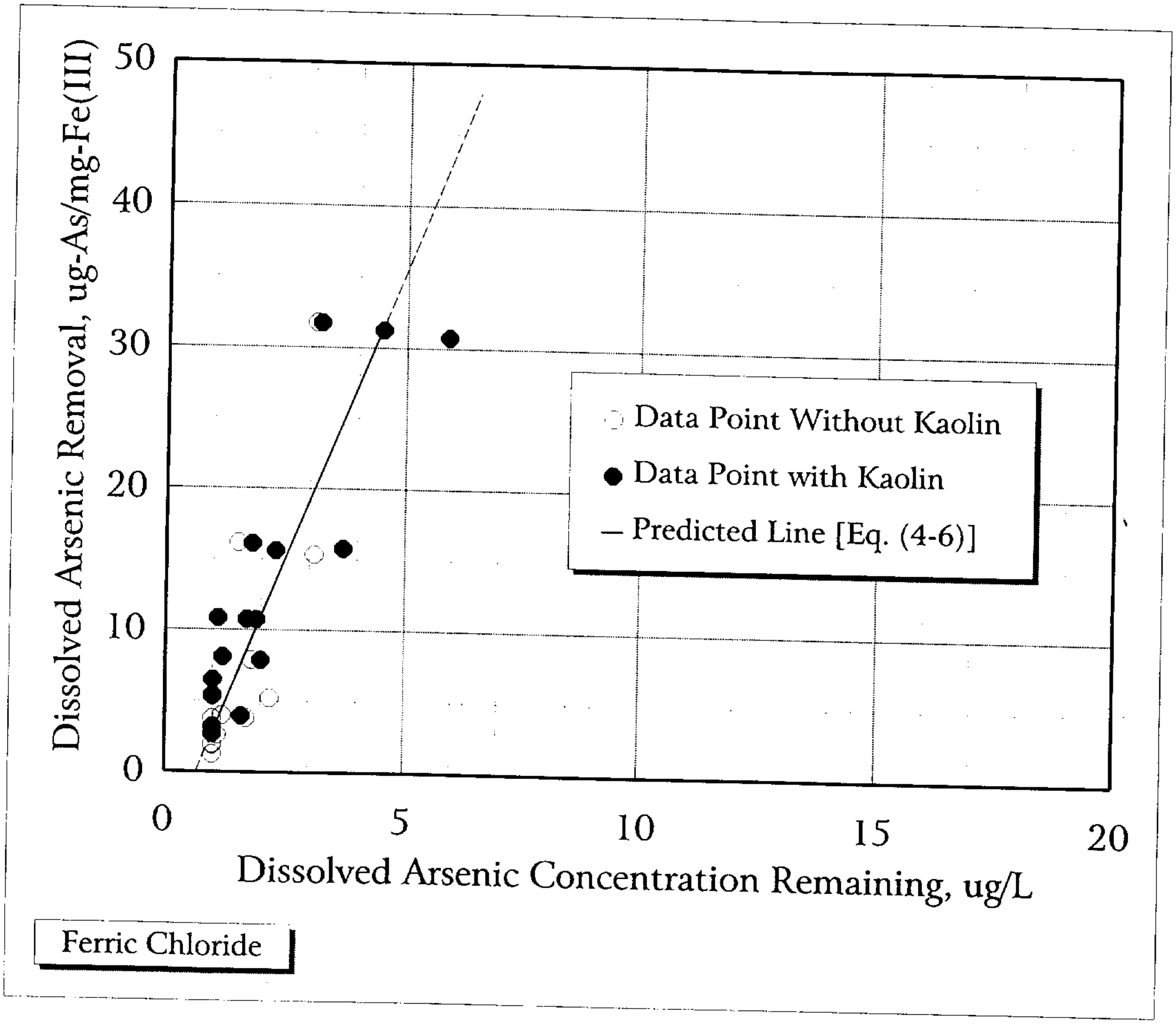


FIGURE 4-33

Relationship Between Amount of Dissolved Arsenic Removal and Dissolved Arsenic Concentration Remaining

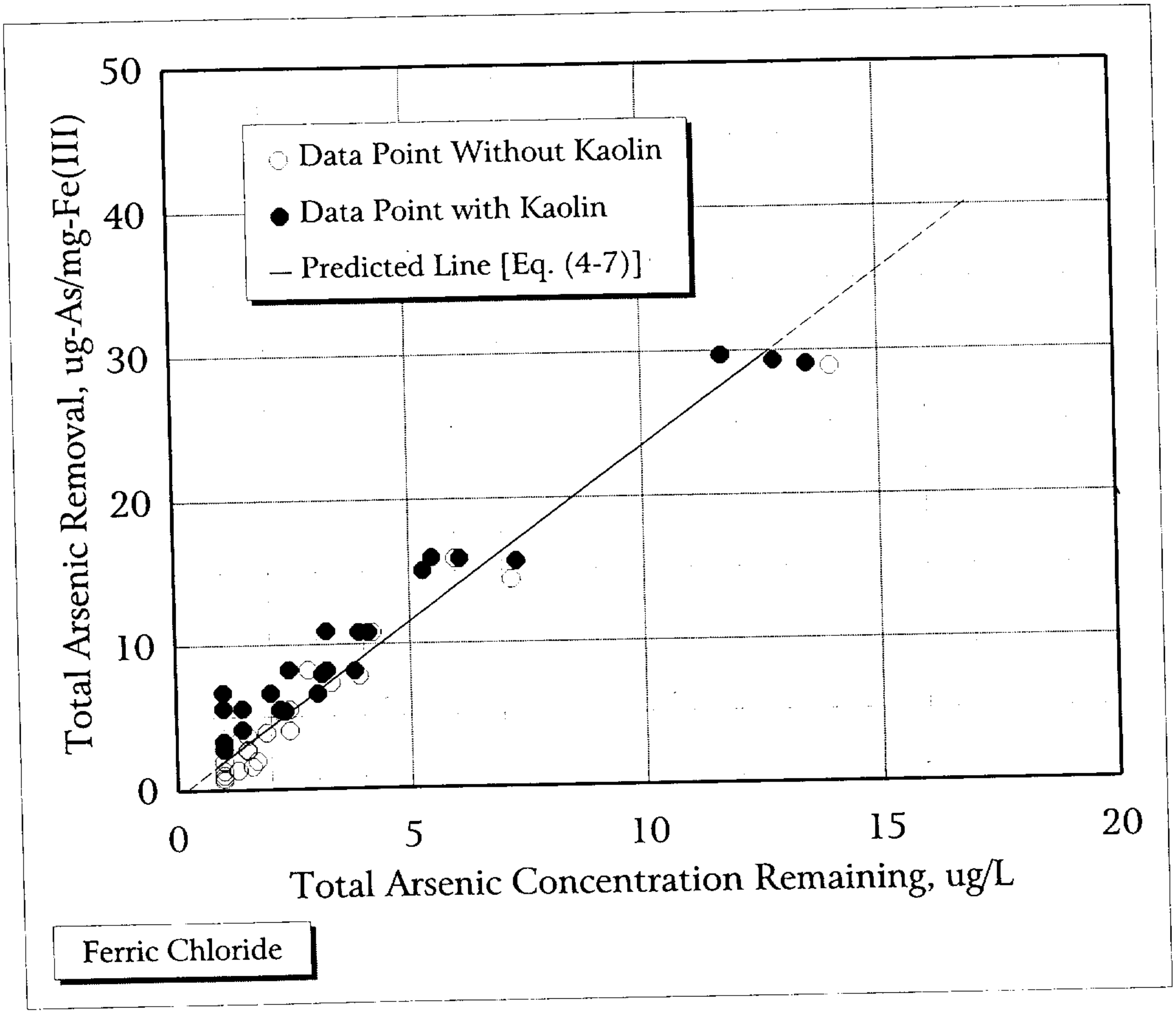


FIGURE 4-34

Relationship Between Amount of Total Arsenic Removal and Total Arsenic Concentration Remaining

A regression line almost passes through the origin with a positive intercept of 0.19 μg/L on the horizontal axis. This small value may be caused by experimental error. It is also noted that the slope of the line [Eq. (4-6)] is 2.40 μg-As/mg-Fe(III) per μg-As/L. This value is 3.4 times smaller than the slope of the line expressed by Eq.(4-6) (8.21 μg-As/mg-Fe(III) per μg-As/L). The higher value of the slope in Eq. (4-6) implies a dominant influence of Step 1 on the removal of dissolved arsenic. However, the efficiency of total arsenic removal is significantly decreased due to the effect of Step 2.

EFFECT OF INITIAL ARSENIC CONCENTRATION ON THE REMOVAL OF ARSENIC

The removal of arsenic from water may be significantly influenced by the initial arsenic concentration in raw water due to the strong dependence upon the mechanisms involved in Step 1. Since dissolved and total arsenic removals have similar trends, dissolved arsenic is used as an example to show the effect of initial arsenic on the arsenic concentration remaining in the solution. The initial total and dissolved arsenic concentrations are assumed to be identical in raw water. By rearranging Eq. (4-6), the minimum achievable arsenic concentration remaining in the treated water is generalized by Eq. (4-8). This relationship is shown in Figure 4-35.

$$[\text{Arsenic}]_{\text{remaining}} = \frac{[\text{Arsenic}]_{\text{initial}} + 5.45 \times [\text{ Dosage }]_{\text{Fe(III)}}}{1 + 8.21 \times [\text{ Dosage }]_{\text{Fe(III)}}} \qquad (4 - 8)$$

where, $[\text{Arsenic}]_{\text{remaining}}$ = minimum achievable dissolved arsenic concentration remaining (μg/L)

$[\text{Arsenic}]_{\text{initial}}$ = initial total arsenic concentration (μg/L).

It is clearly shown in Figure 4-35 that even at a 50 μg/L initial concentration, a dissolved arsenic concentration lower than 2 μg/L in finished water may be achieved at an Fe(III) dosage as low as 4 mg/L. It is assumed that no impurity interferes with the immobilization of arsenic onto the ferric hydroxide precipitates in Step 1, and that a perfect separation of arsenic-carrying particles is achieved in Step 2. In water treatment practice, however, these ideal conditions may not exist. The overall removal of arsenic may be decreased significantly in both steps. Therefore, enhanced coagulation must achieve a high overall removal of arsenic ($E_{overall}$) through two approaches: (1) enhanced removal of arsenic in Step 1 (E_1) by improved adsorption and/or coprecipitation mechanisms and (2) enhanced separation of arsenic-carrying particles in Step 2 (P_2) by improved coagulation, flocculation, and sedimentation processes. The optimum Fe(III) dosage for arsenic removal may therefore vary, depending upon the raw water quality and design and operational features of the plant.

Based on the concepts presented above, two generalized equations have been developed: Equations (4-9) and (4-10). These equations can be used to calculate the maximum achievable amount of arsenic removed, and the removal rate of arsenic from raw water containing any given concentration of total arsenic.

$$[\text{Arsenic}]_{\text{amount, removed}} = \frac{(-5.45 + 8.21 \times [\text{Arsenic}]_{\text{initial}}) \times [\text{Dosage}]_{\text{Fe(III)}}}{1 + 8.21 \times [\text{Dosage}]_{\text{Fe(III)}}} \qquad (4-9)$$

$$[\text{Arsenic}]_{\text{rate, removed}} = \frac{(-5.45 + 8.21 \times [\text{Arsenic}]_{\text{initial}}) \times [\text{Dosage}]_{\text{Fe(III)}} \times 100\%}{(1 + 8.21 \times [\text{Dosage}]_{\text{Fe(III)}}) \times [\text{Arsenic}]_{\text{initial}}} \qquad (4-10)$$

where $[\text{Arsenic}]_{\text{amount, removed}}$ = amount of arsenic removed (μg-As/L)

$[\text{Arsenic}]_{\text{rate, removed}}$ = arsenic removal rate on the basis of initial total arsenic concentration (percent).

EFFECT OF INITIAL TURBIDITY ON THE REMOVAL OF ARSENIC

In this study, the effect of the initial turbidity level on the total removal of arsenic was investigated with kaolin-spiked tap water. The initial turbidity levels used in the experiments were roughly 0, 10, 20, and 40 NTU. The experimental results show no defined effect of turbidity in the range of 0 - 30 NTU on the total removal of arsenic. There was slightly improved total arsenic removal if the initial turbidity was 40 NTU. These results are shown in Figure 4-36. The total arsenic removal at a higher turbidity may be improved due to (a) enhanced sweep-coagulation caused by formation of large amounts of floc at high turbidity and (b) extra-active sites for adsorption of arsenic onto the surface of clay particles. At a low initial turbidity, enhanced total arsenic removal

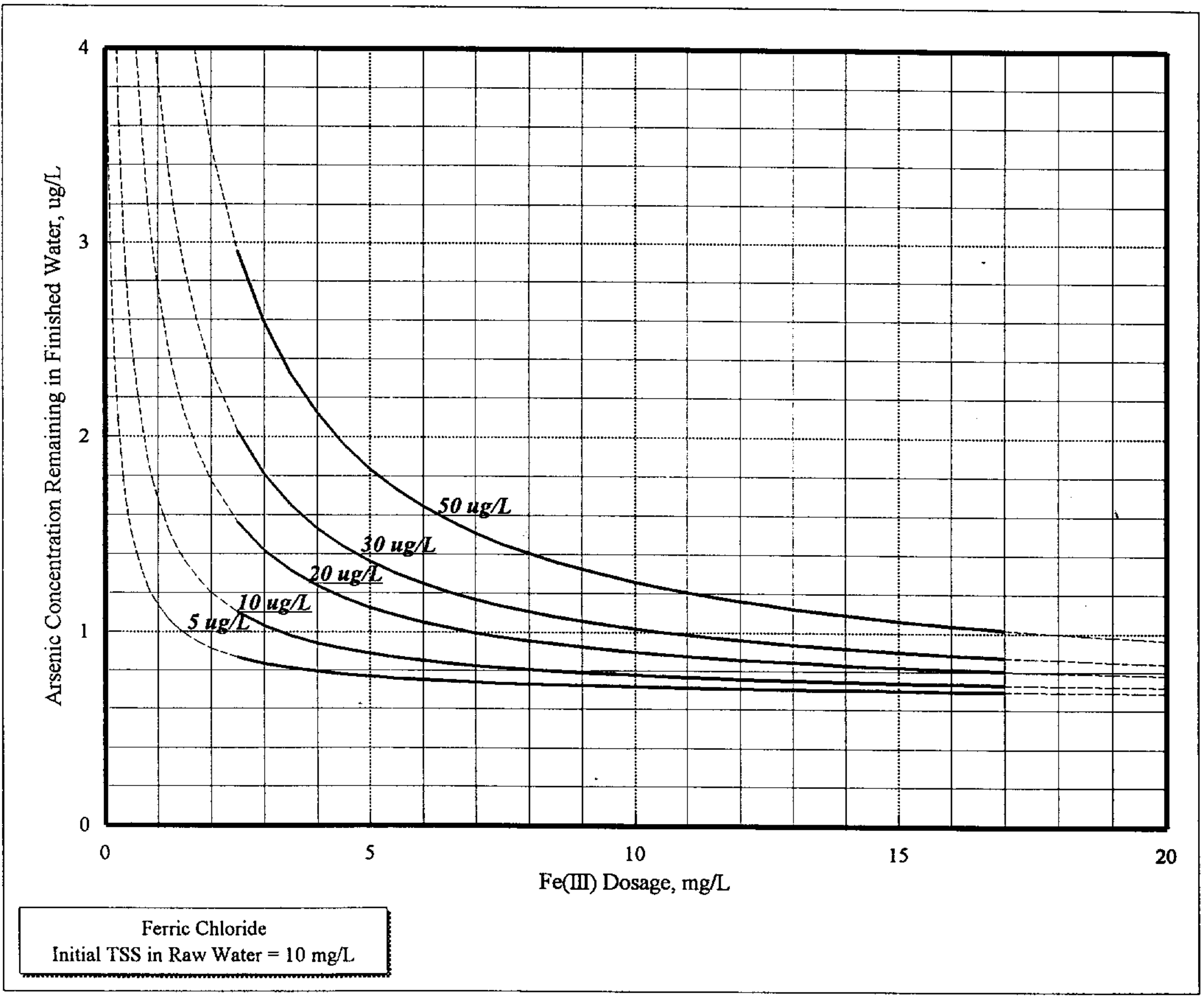
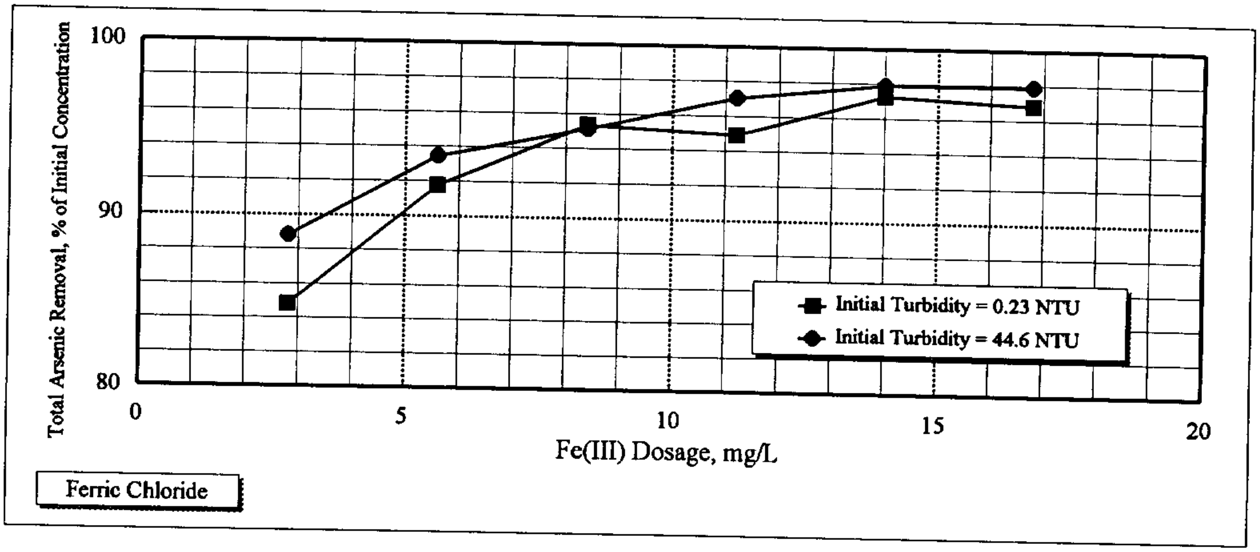
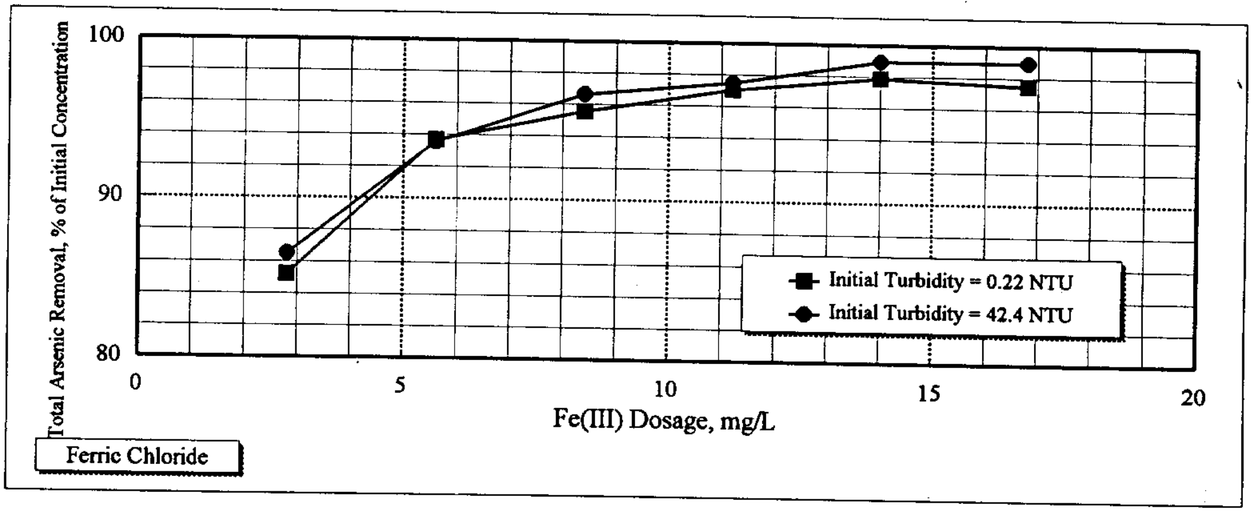


FIGURE 4-35

Minimum Achievable Arsenic Concentration Remaining in Finished Water



(a) Initial Total Arsenic Concentration = 47.4 μg/L



(b) Initial Total Arsenic Concentration = 94.8 μg/L

FIGURE 4-36

Effect of Initial Turbidity on Total Arsenic Removal in Settled Water due to these mechanisms may be ineffective. The adsorption of arsenic onto clay particles has been reported in another study in soil science (Frost and Griffin 1977). In this study, the enhanced removal of arsenic by adsorption may be limited due to (a) kinetic limitation between the arsenic species and clay particles within a very short contact time (30 seconds rapid mixing plus 25 minutes flocculation) and (b) the relatively low adsorption capacity of clay in competition with iron hydroxide. In conclusion, clay-based turbidity-causing materials actually have a positive effect on the removal of total arsenic when these materials are effectively removed from the water. However, the natural turbidity-causing materials consist not only of clay-based inorganic particles, but also of other non-clay portions. Natural organic matter is also one of the most important components of natural turbidity and may compete with arsenic for adsorption onto the amorphous ferric hydroxide in the coagulation process. Further studies are needed to substantiate these results.

Chapter 5

PHOTOCATALYTIC TREATMENT OF As(III)-CONTAINING WATER

Several bench-scale proof-of-concept experiments were conducted to investigate the applicability of the advanced oxidation/reduction process for pretreatment of As(III)-containing water. Two new technologies for changing the oxidation state of arsenic species were investigated. These two approaches are (1) photocatalytic oxidation of As(II) to As(V) and (2) photocatalytic reduction of As(III) to As(0). Encouraging results were obtained with both technologies in this study.

The experimental program and results are presented below.

5.1 EXPERIMENTAL PROGRAM

The experimental program for the development of technologies included material and experimental protocols.

5.1.1 MATERIALS

In this study, an arsenite solution of approximately 40 ppm was prepared from arsenic trioxide, As_2O_3, under acidic conditions (pH ~ 1). This virgin solution was then utilized in the experiments for either oxidation or reduction purposes.

Anatase (TiO_2) samples used were Degussa P-25, comprised predominantly of the anatase modification with ca. 20 percent rutile as estimated by Raman spectroscopic analysis. The specific surface area of these particles was ca. 60 m^2/g (as measured by BET analyses) corresponding to particles in the μm-diameter range.

5.1.2 EXPERIMENTAL PROTOCOL

A batch photocatalytic reactor was used in this study. Figure 5-1 illustrates a schematic of the experimental setup for both As(III) oxidation and reduction. The same reactor was used both in the dark (for H_2O_2 oxidation) and under illumination of light.

The experimental protocols for As(III) oxidation and reduction are presented separately below.

As(III) Oxidation

In the As(III) oxidation experiments, the AOPs considered were UV/TiO_2, homogeneous oxidation with H_2O_2, and heterogeneous UV/H_2O_2 photolysis. A medium-pressure Hg lamp (400 W) was used in the latter case, with a radiant output of 1.83×10^{-5} Einsteins/min as assayed by ferrioxalate actinometry. The arsenite [As(III)]-spiked water sample was loaded into the reactor, and the pH was adjusted to ~9 with NaOH. The purge gas (air or N_2) was turned on, and the gas flow (at ca. 200 mL/min) also agitated the solution and optimized the mass transfer and suspension of TiO_2 particles (for the UV/TiO_2 experiments) in the water.

The nominal As(III) load of the water samples was 39.4 mg/L. Sample aliquots were periodically withdrawn from the reactor and analyzed for As(V) conversion via ion chromatography.

As a part of this study, a proof-of-concept experiment was also conducted to demonstrate the feasibility of the photocatalytic coagulation approach. In the preliminary experiments, arsenite was first oxidized to arsenate by using H_2O_2 or the photocatalytic method. The pretreated water was then coagulated with ferric ions. The precipitate was separated and the clear solution was measured by UV/VIS spectroscopy to determine the residual amount of arsenate.

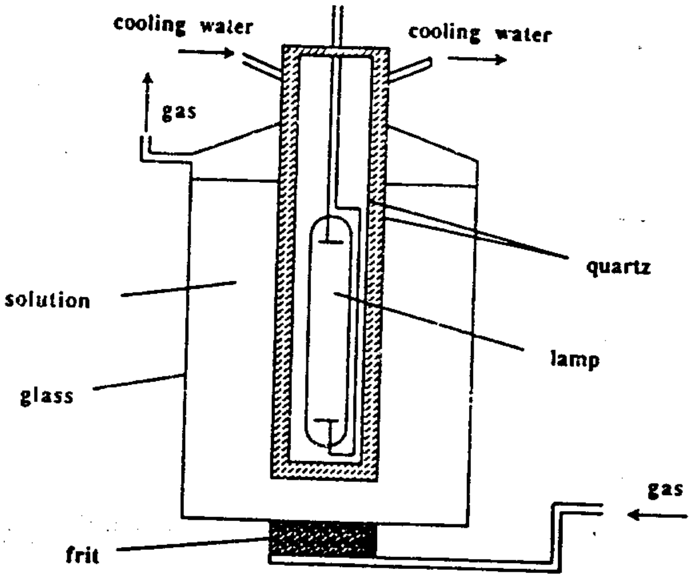


FIGURE 5-1

Schematic Experimental Setup

As(V) Reduction

In this study, the ARP utilized was UV/TiO_2. To prove this concept, 40 ppm of arsenite in an acidic (pH $\sim$1) solution was prepared as a virgin solution. This solution was then treated with TiO_2 (4.4 g/L) in the dark and under illumination for two hours in each period.

5.2 RESULTS AND DISCUSSION

In this section, the experimental results on photocatalytic technologies are presented and discussed in regard to two major approaches: (1) photocatalytic oxidation of arsenite to arsenate and (2) photocatalytic reduction of arsenite to arsenic.

5.2.1 PHOTOCATALYTIC OXIDATION OF ARSENITE

Proof-of-concept experiments have been completed for the applicability of advanced oxidation processes (AOPs) for the pretreatment of As(III)-containing water samples.

Figure 5-2 summarizes the key findings from the UV/TiO_2 experiments. The points represent the experimental data, and the curves are simply drawn through the data points. The two sets of curves at the bottom are control runs wherein the As(III)-containing solutions were exposed to TiO_2 in the presence of N_2 and air with no UV irradiation of the semiconductor particles. Incipient air oxidation manifests as a small upward slope of the "TiO_2/Air" data.

Interestingly, heterogeneous photocatalysis with TiO_2 results in the conversion of only ca. 50 percent of the original As(III) present. This is rationalized on the basis of the schematic in Figure 5-3. Bandgap irradiation of the TiO_2 particles results in the generation of e^-h^+ pairs. The holes oxidize the surface hydroxyl groups to form the high-reactive $^{\bullet}OH$. The latter oxidizes As(III) to As(V). Direct oxidation of As(III) by the photo-generated holes also cannot be ruled out. On the other hand, in the absence of a suitable electron acceptor (e.g., O_2), many of the e^-h^+ pairs simply recombine. Thus, the available hole flux is insufficient to oxidize all of the As(I) present. In the presence of air, rapid oxidation of As(III) ensues and complete conversion is attained within ca. 20 minutes of irradiation. The TiO_2 dose in the experiments in Figure 2 was 1 g/L.

Next, the oxidation of As(III) by H_2O_2 in the dark was probed. Note that H_2O_2 is a powerful oxidant with the standard reduction potential E° given by the following:

$$E^\circ = 1.78 - 0.0592\ \text{pH} \qquad (5-1)$$

For the pH 9 solutions employed here, E° translates to 1.25 V. The As(III)/As(V) redox reaction has a standard potential given by the following:

$$E^\circ = 0.56 - 0.0592\ \text{pH} \qquad (5-2)$$

Thus, E° is 0.029 V at pH 9 for the negative of the H_2O_2/H_2O redox potential. Therefore, the driving force for electron transfer is appreciable.

Figure 5-4 contains data wherein the As(III):H_2O_2 mole ratio was used as a parameter. An excess of H_2O_2 is seen to be required to bring the As(III) oxidation to completion. At a fixed As(III) level, an increase in the H_2O_2 concentration moves its redox potential in the positive direction, thus enhancing the driving force for electron transfer.

With UV irradiation of the H_2O_2 solution, the oxidation of As(III) is virtually instantaneous even at ratios as low as As(III):H_2O_2 (Figure 5-5). Irradiation causes H_2O_2 photolysis:

$$H_2O_2 \xrightarrow{hv} 2\ {}^\circ OH. \qquad (5-3)$$

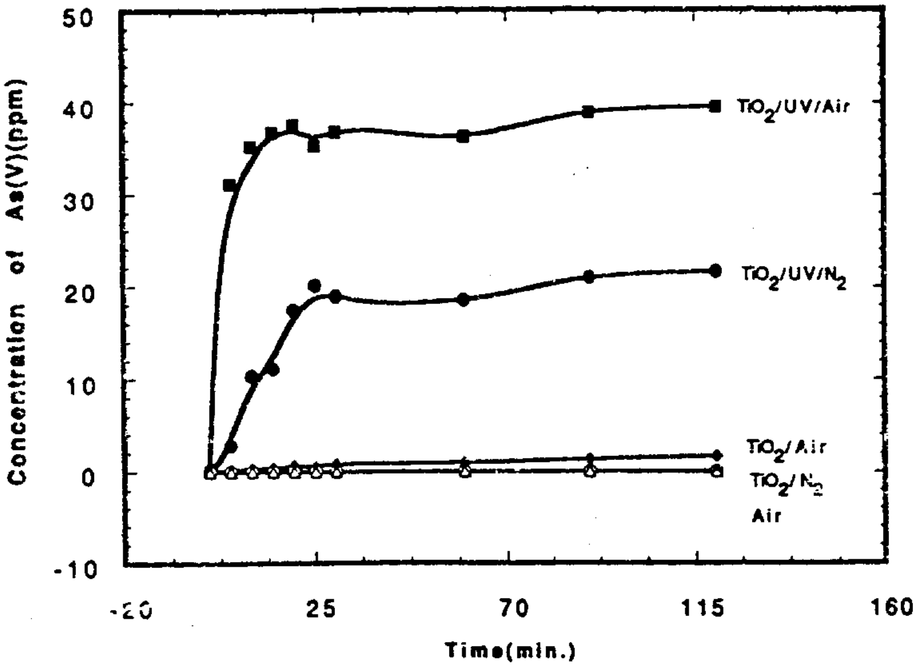


FIGURE 5-2

Conversion of As(III) to As(V) by the TiO_2/UV Oxidation Process in a Batch Reactor

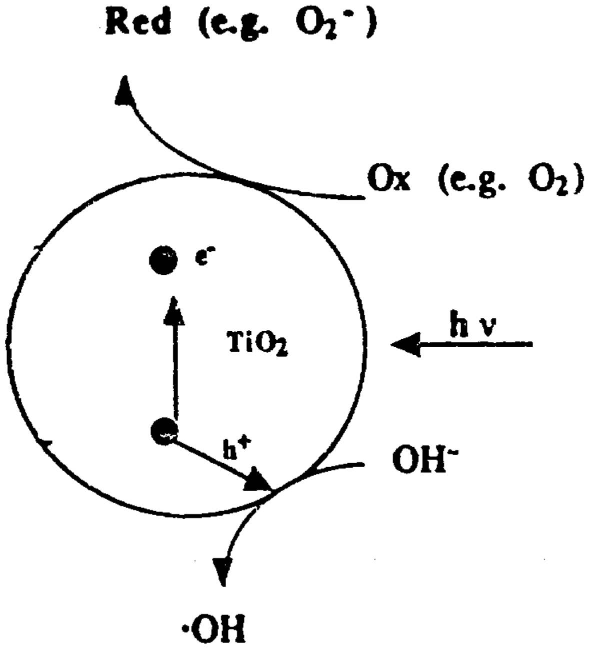


FIGURE 5-3

TiO_2 Photocatalytic Scheme for Enhanced Oxidation of As(III) to As(V)

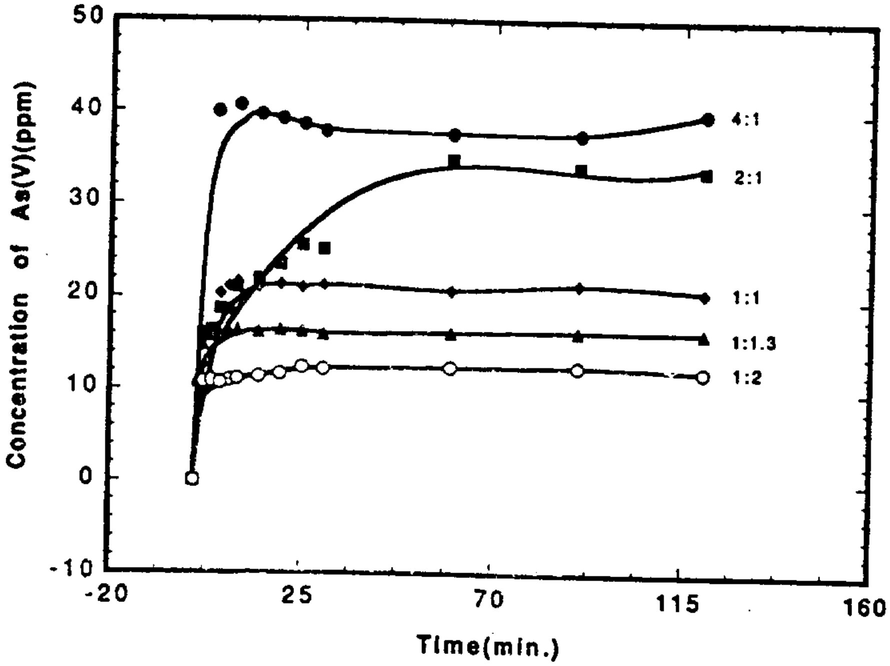


FIGURE 5-4
Conversion of As(III) to As(V) Without UV Irradiation at Different H_2O_2:As(III) Mole Ratios

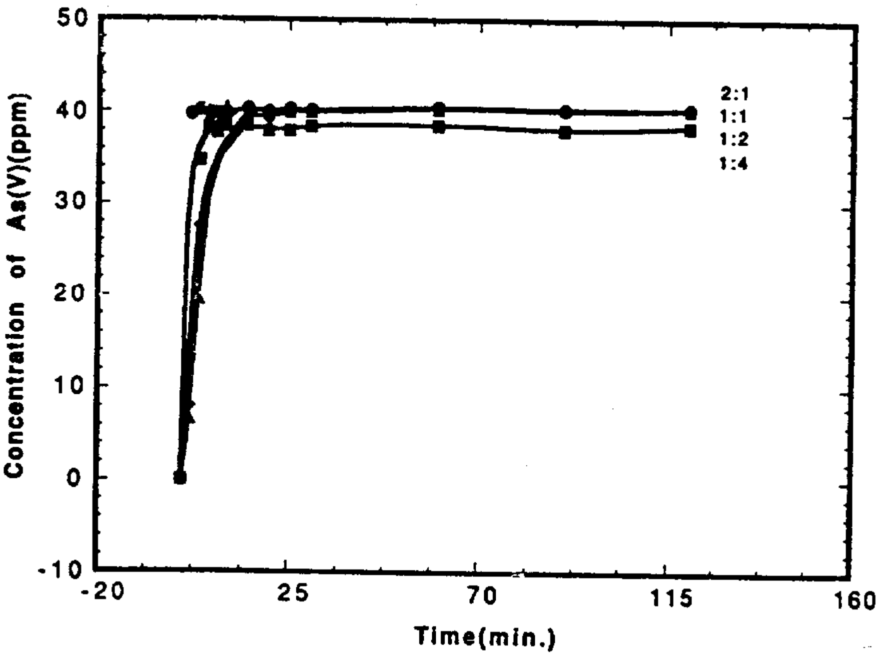


FIGURE 5-5

Conversion of As(III) to As(V) with UV Irradiation at Different H_2O_2:As(III) Mole Ratios

And the radical oxidation route serves to enhance the As(III) oxidation several fold. Future plans in this area include the following:

- (a) The use of As(III) and pH as process variables
- (b) The addition of Fe^{2+} ions and the coagulation of As(V) as the ferric salt
- (c) The use of flow streams containing As-polluted water

It is also to be noted that the As levels considered in this bench study are considerably higher than practical levels. However, these baseline studies provide fundamental understanding of the process chemistry without the analytical complications of dealing with ppb levels of arsenic. Longer-term studies will address the practical aspects.

Preliminary experiments with the photocatalytic coagulation approach were also conducted. However, as Figure 5-6 shows, the presence of residual ferric ions caused a spectral interference. Further experiments are needed so that the solution level of total arsenic can be monitored by atomic absorption spectroscopy. Lamp sources for arsenic analyses by this method are not available to us at present.

5.2.2 PHOTOCATALYTIC REDUCTION OF ARSENITE TO ARSENIC

A novel approach to the one-step removal of arsenic is to use photocatalytic reduction of As. The relevant equations are as follows:

$$HAsO_2(aq) + 3\,H^+ + 3\,e^- \rightarrow As + H_2O \qquad E^\circ = +0.248\ V \qquad (5-4)$$

$$H_3AsO_4 + 2\,H^+ + 2\,e^- \rightarrow HAsO_2 + 2\,H_2O \qquad E^\circ = +0.560\ V \qquad (5-5)$$

Both redox potentials are positive and lie beneath the conduction band of TiO_2. This means that arsenic can easily accept electrons from the illuminated TiO_2 particles and be reduced on particle surfaces. The arsenic is thus immobilized from the process stream.

Figure 5-7 shows the results of this experiment. Arsenite appears at very short wavelengths, around 200 nm, with absorbance of about 1.5 AU before treatment (Figure 5-7a). However, the peak shifts to around 265 nm, with absorbance at about 1.0 AU, after the addition of TiO_2 in the dark for two hours (Figure 5-7b). The lower absorbance in this case may be due to the adsorption of arsenite onto the TiO_2 surface, although the origin of the peak shift requires further study. Under the illumination of UV light, the absorbance was further reduced to about 0.75 AU, and the peak shifted to about 270 nm (Figure 5-7c). The difference in the absorbance between Figures 5-7b and 5-7c can be converted to the concentration difference of arsenite in solution. About 16.7 percent (or 6.68 ppm) of arsenite was reduced from the solution during the illumination with UV light.

Because of the ambiguity associated with direct spectrophotometric assay of arsenic, recourse was sought by an indirect method. This method is based on the formation of an ion pair between arsenomolybdate and a large dye cation such as Rhodamine B. Figure 5-8 contains representative spectra obtained from standard As(V) solutions to which ammonium molybdate and Rhodamine B were added. This indirect method has good sensitivity down to ~0.2 μg/25 mL.

At the time of compilation of this report, this analytical protocol was being refined and optimized in our laboratory. However, the results to date show that TiO_2 in acidic media strongly adsorbs arsenic even in the dark. Presumably, at pH values positive of the point-of-zero charge (~5.5 for TiO_2), the TiO_2 surface, because it is positive charge electrostatically, binds the negatively charged arsenic species.

Experiments employing UV-irradiated TiO_2 aimed at further immobilizing arsenic via photocatalytic reduction are in progress. Again, the preliminary data are very encouraging (Figure 5-9).

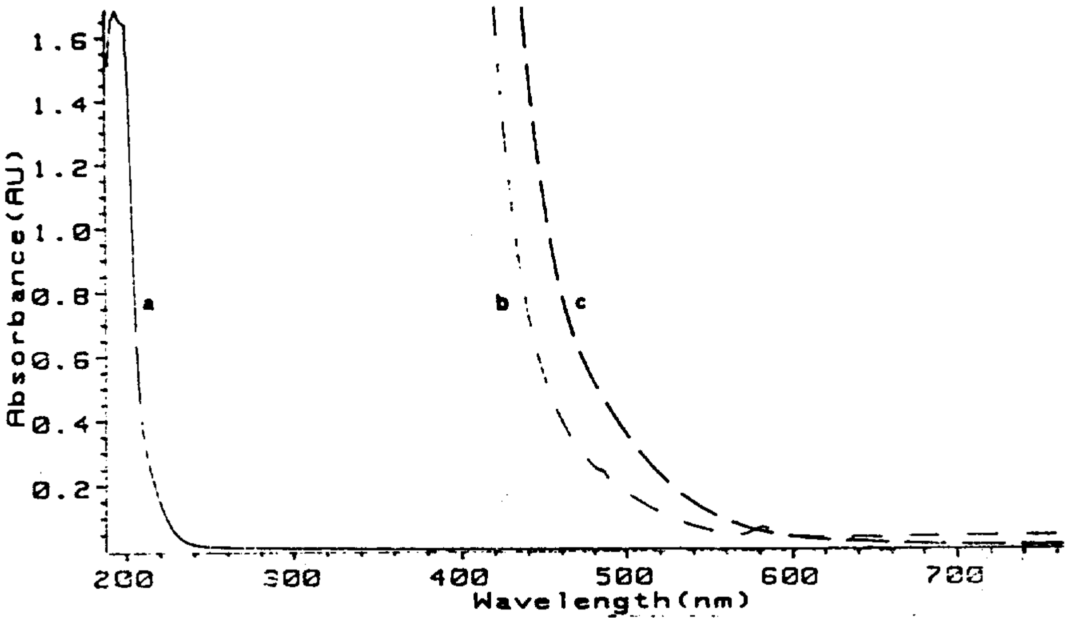


FIGURE 5-6

UV Spectrum of Arsenate with and Without $FeCl_3$:
(a) 40 ppm As(V) w/o $FeCl_3$
(b) with addition of $FeCl_3$
(c) after stirring and precipitation

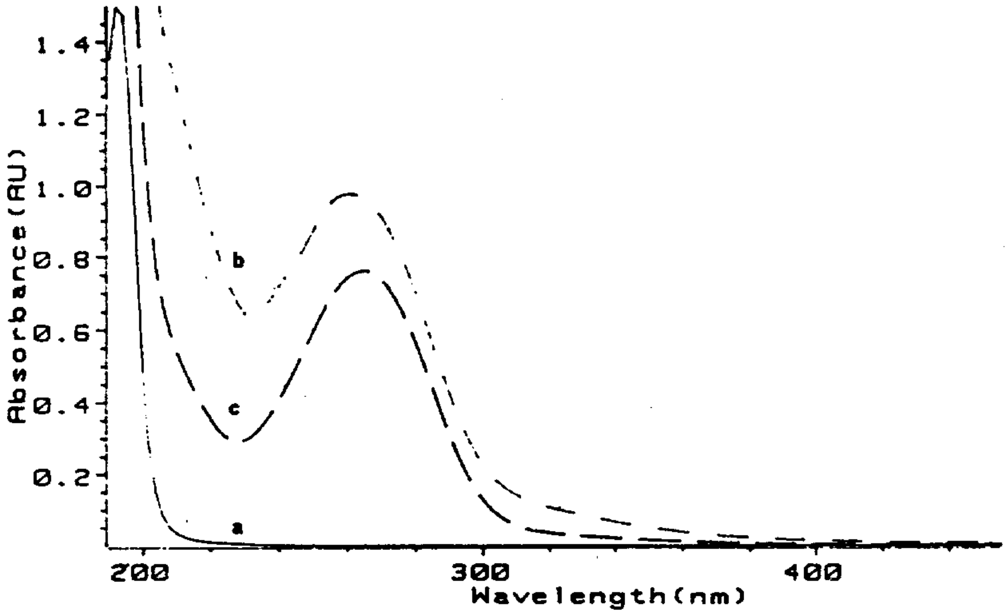


FIGURE 5-7

UV/Vis Spectrum of Photocatalytic Reduction of Arsenic
at TiO_2 Particles in Acidic Solution
(a) 40 ppm As(III) in original solution
(b) 40 ppm As(III) solution with 4.4 g/L at TiO_2 *in dark for 2 hours*
(c) solution b under UV light illumination for 2 hours

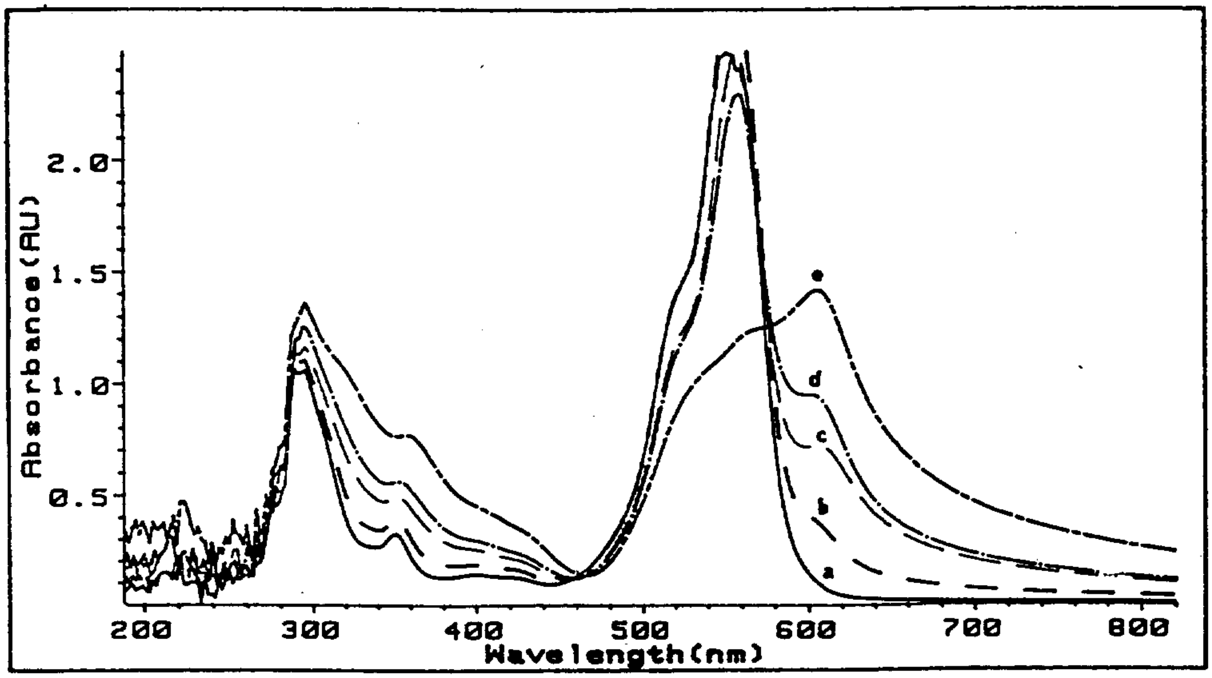


FIGURE 5-8

Absorption Spectra of Arsenomolybdic Acid ~ Rhodamine B
[Rhodamine B (0.02%) 2.5 mL; Ammonium Molybdate (0.5%) 1 mL; and
Polyvinyl Alcohol (0.1%) 2 mL]

(a) Zero
(b) 0.1 ppm
(c) 0.2 ppm
(d) 0.4 ppm
(e) 0.8 ppm

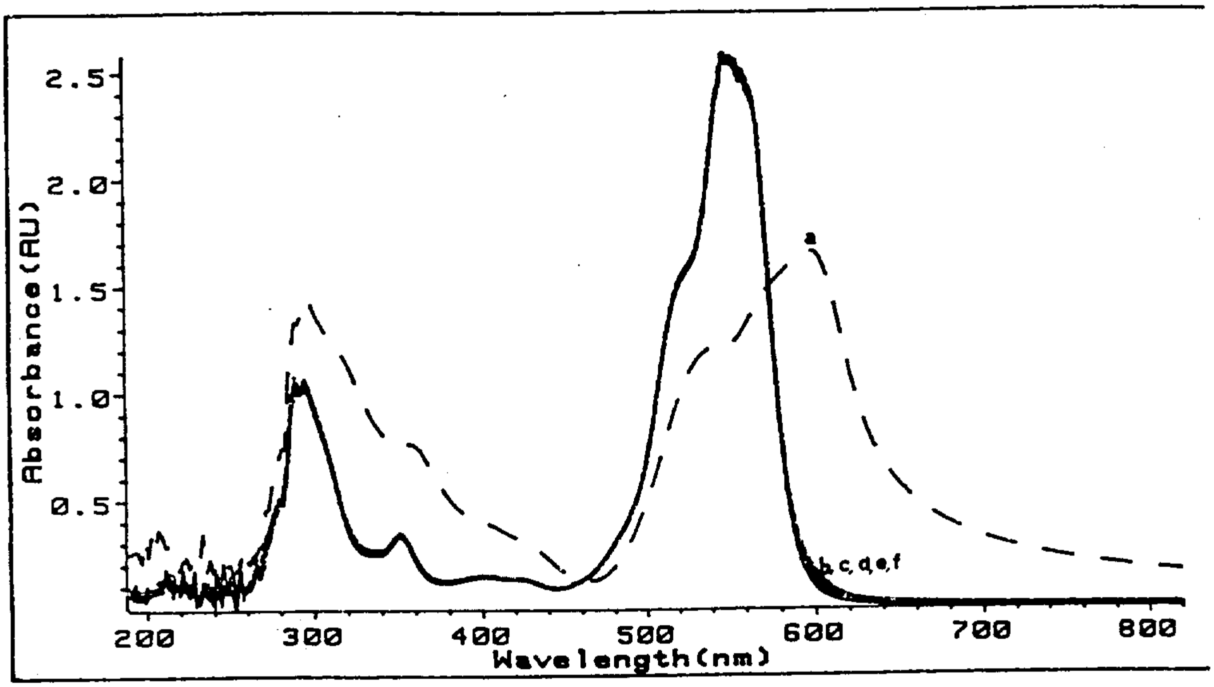


FIGURE 5-9

Absorption Spectra of Arsenomolybdic Acid - Rhodamine B Before and After the Reaction of As(V) with TiO_2/UV Light

(a) original solution contains 4 ppm at As(V)
(b) addition of 2.2 g/L of TiO_2 in the solution for overnight under dark
(c) solution irradiated with UV light for 30 min.
(d) solution irradiated with UV light for 60 min.
(e) solution irradiated with UV light for 90 min.
(f) solution irradiated with UV light for 120 min.

Chapter 6
PILOT PLANT STUDIES FOR ARSENIC REMOVAL

6.1 PURPOSE AND SCOPE OF STUDY

In order to confirm the findings of the bench-scale jar test efforts, a series of pilot-scale tests was conducted. The pilot plant located at the Rolling Hills Water Treatment Plant (RHWTP) in Fort Worth, Texas, was used to run the experiments. The pilot-scale tests were designed to duplicate some of the jar tests and to focus specifically on treatment schemes that produced favorable results at the bench scale. The first step was to test a matrix of different treatment conditions which would allow a comparison of the findings of the bench-scale and pilot-scale tests. The variables in the initial test matrix included the following items:

- Coagulation at different doses of ferric sulfate
- Coagulation at different pH values (including lime softening)

The next step in pilot plant testing was to focus on the results of the initial matrix and to run additional tests at the points of optimum arsenic removal. These additional tests were also limited to operational conditions which were the most practical for municipal water treatment. The tests examined the effects of the following variables on arsenic removal:

- Two primary coagulants: ferric sulfate and ferric chloride
- Coagulation with and without cationic polymer
- Coagulation with and without preozonation
- Different arsenic species (As^{+3} vs As^{+5})

In addition to providing a comparison for the jar tests, the pilot plant tests are useful for determining the cost and practicality of full-scale treatment schemes. Because the pilot plant more closely simulates full-scale water treatment, the chemical and energy costs can be more accurately scaled to project a full-scale operational budget.

6.2 PILOT PLANT DESCRIPTION AND DESIGN

6.2.1 PROCESS TRAIN

The pilot plant was designed for a continuous 6 gallons per minute (gpm) flow rate. The pilot plant includes a constant-head weir box, a preozonation chamber, dual rapid mix chambers, a three-stage flocculation basin, a gravity settling tank, and dual media filters. The flow scheme and sampling locations for the pilot plant study are shown in Figure 6-1.

The detention time for the ozone contact chamber is approximately 19 minutes at 6 gpm. The G value for each stage of the rapid mix chambers was approximately 483/sec. The three stages of the flocculation basin had G values of 60/sec, 40/sec and 20/sec, in descending order. The sedimentation tank had a detention time of approximately 3.5 hours, with a surface loading of 247 gallons per day per square foot. The filters were loaded at approximately 6 gpm per square foot. Further details about the RHWTP pilot plant are provided in Appendix G.

6.2.2 CHEMICAL FEED SYSTEMS

6.2.2.1 Coagulants

Iron-salt coagulants such as ferric sulfate react with untreated water to form ferric hydroxide, which under normal treatment conditions forms a solid. These solids to form floc particles which settle out of the water column and sweep much of the suspended material in the water to the bottom of the sedimentation basins, where it is removed. Without a coagulant such as ferric chloride, it would be impossible to meet state and federal requirements for treated water turbidities.

CONSTANT HEAD TANK
W x L x D: 12" x 18" x 24"
Q = 6 GPM

CHEMICAL FEED PUMPS:
8-UNITS
1/10 H.P. EACH
- VARIABLE SPEED

OZONE CONTACT CHAMBER
W x L x D: 21" x 23" x 4'-6"
DETENTION TIME: 10 MINUTES
DIFFUSER: 1
POROUS CERAMIC STONE
INJECTOR:
MAZZIE INJECTOR/PUMP
COMBINATION

RAPID MIXING CHAMBERS
2 - COMPARTMENTS
W x L x D: 12" x 12" x 13.5"
DETENTION TIME = 1.4 MINS. EACH
Q = 6 GPM
MIXERS:
2-UNITS
1/15 H.P. - VARIABLE SPEED

FLOCCULATION TANKS
1 - TANK
W x L x D: 2' x 6'-6" x 2'
DETENTION TIME: 33 MINUTES(TOTAL)
Q = 6 GPM
FLOCCULATORS
3 STAGES
1/15 H.P. - VARIABLE SPEED

SEDIMENTATION TANKS
1 - TANK
W X L X D: 2.5' X 7' X 6.75'
DETENTION TIME: 3.5 HOURS
Q = 3 GPM

SETTLED WATER TANK
2 - TANKS
W x L x D: 12" X 12" X 16"
DETENTION TIME: 3.3 MINUTES
Q = 3 GPM

RELIFT PUMPS:
3-UNITS
Q = 0.17 TO 3.5 GPM
1/4 H.P. - VARIABLE SPEED

FILTER COLUMNS
3 - COLUMNS
DIA. x L: 4" x 8'
MAX. FILTER LOADING RATE: 15 GPM/FT²
BACKWASH WITH AIR SCOURING

AIR COMPRESSOR
1 - UNIT
1/2 H.P.
FLOW = 4 CFM
RECEIVER TANK VOLUME= 60 GALLONS

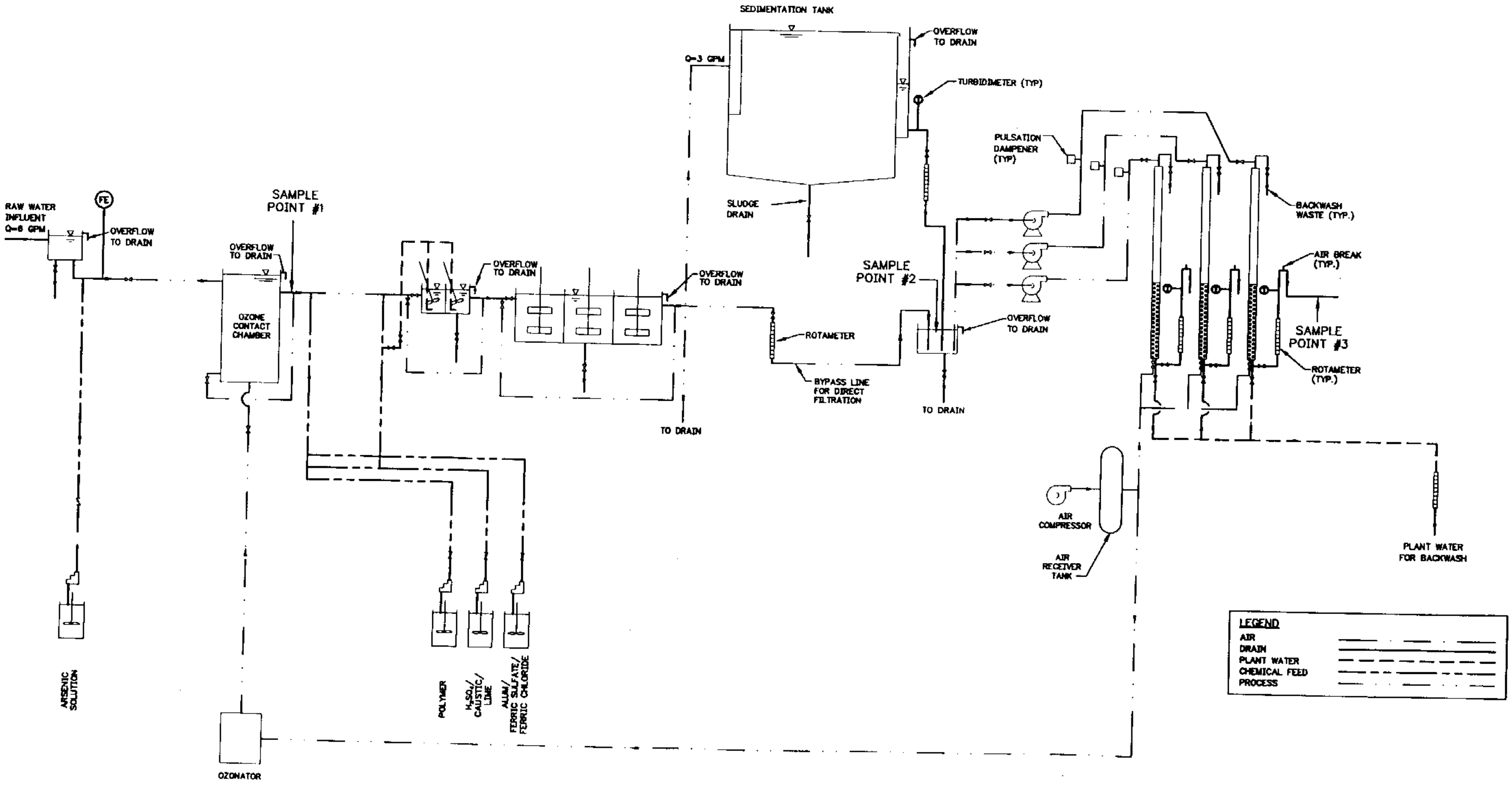


Figure 6–1
Process Train of the
Pilot Plant Facility

The coagulants used for the pilot plant in this study were ferric sulfate and ferric chloride. Approximately two-thirds of the pilot plant runs for this study were made using ferric sulfate as the primary coagulant. About one-third of the runs were made using ferric chloride to determine whether there were any significant differences between the two coagulants.

Both coagulants were fed by a peristaltic pump directly to the first stage rapid mixer. The pump was calibrated daily to feed the proper dosage. The coagulant solution was made the day before each run and was diluted to a volume of 60 liters with deionized water. The amount of coagulant was matched to one of three doses which were used in the jar tests. The doses were based on liquid ferric sulfate solution doses of 30, 60, and 90 milligrams per liter (mg/l). The dosage was then converted to the equivalent iron content based on the percent iron concentration supplied by the chemical manufacturer (10.5% for the liquid ferric sulfate and 13.7% for the liquid ferric chloride). The equivalent ferric chloride dose could then be calculated for an equivalent ferric ion (Fe^{+3}) content. The majority of the runs were conducted with a ferric iron dose of 6.3 mg/l, which is equivalent to a 60 mg/l liquid ferric sulfate dose or a 46 mg/l liquid ferric chloride dose.

6.2.2.2 pH Adjustment

The pH of the final filtered water was targeted to be one of the values of 5.0, no adjustment (usually around 7.0), 8.5 or 10.5. Table 6-1 summarizes the chemicals used to adjust the pH of the treated water for the pilot plant studies.

TABLE 6-1

pH ADJUSTMENT CHEMICALS

ADJUSTMENT CHEMICAL	TARGET pH RANGE
Sulfuric Acid	pH < 7.0
Sodium Hydroxide	7.0 > pH > 9.0
Lime	pH > 9.0

The chemical to be used for pH adjustment was measured and diluted to the appropriate concentration the day before each run. Tap water was used to dilute the solutions to a volume of 60 liters. The pH adjustment chemicals were fed by the peristaltic pump directly to the first stage rapid mixer. The amount of each chemical needed to properly adjust the filtered water pH to the target level was not always known. Therefore, some trial and error was necessary to obtain the proper pH. Some runs were not repeated if the pH value was within the range of interest, even if the target pH was not achieved.

6.2.2.3 Arsenic Spiking

The natural background level of arsenic for the raw water entering the pilot plant at the RHWTP averages about 2 to 4 micrograms per liter µg/L. At such low background level of arsenic in raw water, the performance of treatment process was difficult to establish because the current detection limit for arsenic is 1 µg/L. Therefore, it was necessary to simulate the raw water quality with high arsenic levels. This was possible by spiking the raw water sample with arsenic. A known amount of arsenic was dissolved in dechlorinated water and the solution was pumped with a peristaltic pump into the effluent pipe of the constant head box. By pumping the arsenic solution to this point, the turbulence in the pipe was utilized to achieve chemical mixing. The raw water sample was then taken from the contact chamber in which additional mixing was achieved by diffused aeration. The same contact chamber was used for ozone contact in preozonation experiments.

Two sources of arsenic salts were used in this study. Most of the tests were conducted using a hydrated arsenic salt ($Na_2HAsO_4 + 7H_2O$) as the spiking source. The valence of the arsenic in this salt is As^{+5}. Some additional tests were made using arsenic trioxide (As_2O_3) as the spiking source. The valence of the arsenic in this compound is As^{+3}. The arsenate ion (As^{+5}) and the arsenite ion (As^{+3}) are the two most common arsenic species which occur naturally, and they are associated with oxic and anoxic environments, respectively. The tests with both arsenic species were run under identical conditions, except for the change in spiked arsenic species. The difference in the two species responses was evaluated.

The procedure and results presented in this study, therefore, apply to simulated raw water spiked with arsenic. Projection of results for natural water with high background levels of arsenic are covered in Section 6.5.

6.2.2.4 Polymer

Polymer is added to raw water at the rapid mix basins to aid in the process of coagulation. The long polymer molecules help the ferric hydroxide and suspended matter flocculate to form larger particles that are easier to remove. The result is that less primary coagulant is required to achieve the same turbidities.

Cationic polymer was used from the supply of commercial polymer which the RHWTP uses as an aid to coagulation. The polymer used for this study was Cat-Floc DL, manufactured by Calgon, Inc. The dosage used was based on the average feed rate of polymer at the RHWTP. A dose of approximately 1.2 mg/l as liquid polymer was used for each run using polymer. The polymer was measured and diluted with tap water the day before each run and was fed to the first-stage rapid mix basin with a diaphragm metering pump. The pump was calibrated daily to feed the proper dosage.

6.2.2.5 Ozone

Ozone is used in water treatment to disinfect and oxidize raw water, eliminating the need for other disinfectants and improving the water's treatability. Eliminating the need to prechlorinate water is important because it removes the primary source of THMs, which have been closely regulated in the D-/DBP rules. It has also been found that preozonation reduces the amount of chemicals needed to produce the same quality water. For these reasons, preozonation is becoming a popular step in the water treatment process.

Ozone was supplied to the pilot plant by a portable ozone generator. A Griffin Technics Corp. model GTC-1B ozone generator was used in conjunction with a PCI Ozone & Control Systems, Inc., model HC-NEMA 12 ozone monitor to provide an ozone gas stream of 1% by weight concentration. This portable ozone generator operated with pure oxygen (O_2) as the supply gas. The supply pressure of the compressed O_2 forced the ozone into the contact chamber through a 7-1/2-inch-diameter ceramic dome diffuser. Because of the low efficiency of the contactor used at the pilot plant, a relatively high ozone dose of approximately 9 mg/l was applied to the raw water prior to rapid mixing (see Figure 6-1).

6.3 PILOT PLANT PROTOCOL

6.3.1 OPERATIONAL METHODOLOGY

The objective of the pilot-scale testing was to substantiate and refine the information developed during the bench-scale testing. The first series of tests was designed to match ferric sulfate doses and pH values that had been run at the bench scale. This initial matrix of tests provided a comparison between pilot-scale and bench-scale tests as well as indicating which operational points were the most effective at removing arsenic. Further tests were then designed to test the effects of the other treatment variables (e.g., polymer, ozone, etc). Table 6-2 summarizes the matrix of runs and shows the average filtered water pH values that were measured for each run. The pilot plant testing methodology was as follows:

(1) To operate each treatment scenario for a sufficient time to reach a steady state, as indicated by pH, turbidity, alkalinity, and hardness

(2) To take samples of raw, settled, and filtered water from each treatment scenario for chemical analysis

(3) To tabulate and analyze the test results to determine the effectiveness of arsenic removal for each treatment scenario

To ensure that the system had reached a steady state of operation before the first samples were taken, the chemicals for each run were fed continuously to the pilot plant for at least two theoretical detention times (approximately 8 hours) for the entire plant. The chemical pumps were switched on by RHWTP personnel or timer switches at midnight the evening before the next day's testing.

TABLE 6-2
PILOT PLANT TEST MATRIX

Arsenic Species	Coagulant	Polymer	Ozone	Coagulant Dosage (mg/l as Fe(III))	Target pH			
					5.0	Ambient	8.5	10.5
					Average Measured Final pH Values			
V	Ferric Sulfate	No	No	3.2	4.24	7.38	8.91	
				6.3	5.02	7.02	8.13	10.95
				9.5	5.91	6.98	8.23	11.02
		Yes	No	6.3	4.94	6.17	7.46	
		No	Yes	6.3	5.56		8.75	
		Yes	Yes	6.3	5.29		8.76	
	Ferric Chloride	No	No	6.3	6.07		8.52	
		Yes	No	8.2	4.94		7.69	
				6.3			8.43	
		No	Yes	6.3	6.03		8.62	
		Yes	Yes	6.3	5.35		8.50	
III	Ferric Sulfate	No	No	6.3			8.43	
		Yes	No	6.3			8.54	
		Yes	Yes	6.3			8.71	
	Ferric Chloride	No	No	6.3			8.47	
		Yes	No	6.3			8.61	
		Yes	Yes	6.3			8.46	

6.3.2 SAMPLING AND ANALYSIS

Samples of raw, settled, and filtered water were taken at approximately 9:00 a.m., 12:00 noon, and 3:00 p.m. Samples were collected from the ozone contact chamber for raw water, at the clear water tank for settled water, and at the filter effluent for filtered water (see Figure 6-1). The samples were then tested by CP&Y personnel for temperature, pH, turbidity, total alkalinity, and total hardness at the laboratory located inside the RHWTP pilot plant building. Inchcape Testing Service of Richardson, Texas, was retained to conduct total arsenic and TOC measurements. The laboratory staff at RHWTP coordinated the sample delivery and data acquisition as well as performing some TOC measurements.

Each sample was tested for the following properties:

- turbidity
- temperature
- pH
- total alkalinity
- total arsenic

Some samples were tested for the following:

- hardness
- TOC

Hardness was measured only for those samples which had undergone softening due to pH adjustment with lime. TOC was not measured for all samples in order to reduce the cost and effort associated with some of the runs in the preliminary test matrix.

6.4 PILOT PLANT RESULTS AND DISCUSSION

6.4.1 EFFECTS OF pH AND COAGULANT DOSE

Figures 6-2 through 6-10 summarize the results of the runs indicated at the top of Table 6-2 for turbidity and total arsenic measurements. These are the results of the initial test matrix of pilot plant runs without polymer or ozone added to the treatment process.

Generally, the pilot-scale tests indicate better TOC removal at low pH values and better turbidity removal at higher pH values. Both TOC and turbidity removals are better at higher coagulant doses. Arsenic removal is also better at higher doses of the iron-salt coagulants used in this experiment. Arsenic removal is better in settled water at pH values less than 6 and greater than 8. Filtered water arsenic removal is best at pH values around 5 and poorest at pH values around 9. However, the difference in arsenic removal after filtration for the various treatment schemes is relatively small, differing from a best case of 95% removal to a worst case of approximately 80% removal for arsenate (As^{+5}).

6.4.2 CORRELATION WITH JAR TESTS

The results of the pilot plant runs for the settled water show general agreement with the bench-scale jar tests. Both show that arsenic removal is best at pH values below 6 and above 8. Bench-scale and pilot-scale tests both indicate better TOC removal at lower pH values and better turbidity removal at higher pH values. However, the filtered water samples,, do not show the same trends for arsenic removal.

Filters are effective for further arsenic removal at lower pH values, but above a pH value of approximately 9 no additional arsenic removal is accomplished by filtration. However, arsenic levels for settled water with elevated pH values are consistently very low, especially when using lime softening. Therefore, the filtration process seems to equalize the differences in the arsenic content of settled water. The result is that filtered water samples consistently achieve 85 to 95 percent arsenate (As^{+5}) removal and 75 to 85 percent arsenite (As^{+3}) removal without preozonation.

6.4.3 FERRIC CHLORIDE VS FERRIC SULFATE

Several pilot plant tests were set up to evaluate the effect of using ferric chloride as the primary coagulant on the removal of arsenic from drinking water. The purpose of these tests was to compare the effectiveness of ferric chloride and ferric sulfate in removing arsenic. To compare these two coagulants, tests were run which kept all the variables of flow rate, pH, and chemical dosage constant except for the change of primary coagulant. It was necessary to run only a few test configurations to compare the relative effectiveness of ferric chloride and ferric sulfate. When matched for dosage by iron content, there was a slightly higher removal of arsenic in the settled water using ferric chloride. However, no significant differences in arsenic residual were shown in filtered water treated with ferric sulfate and ferric chloride.

Most of the data collected during this study are for ferric sulfate as the primary coagulant. The effectiveness of ferric chloride for arsenic removal in filtered water can be expected to closely match that of an equivalent dose of ferric sulfate when compared by the ferric ion content. Figures 6-11 and 6-14 show the results of comparable runs using the two coagulants.

6.4.4 EFFECTS OF CATIONIC POLYMER ADDITION

Several pilot plant tests were set up to evaluate the effect of adding cationic polymer on the removal of arsenic from drinking water. The addition of polymer has the effect of improving settled water turbidities and appears to increase the removal of arsenic from the settled water. Figures 6-15 and 6-17 show the results of two runs which had similar test conditions, with one having polymer added at the rapid mix chamber. The figures show that even though the settled-water arsenic levels were improved, the filtered-water samples for each run were not significantly different.

6.4.5 PREOZONATION EFFECTS

Several pilot plant tests were set up to evaluate the effect of preozonation on the removal of arsenic from drinking water. The data suggest that ozone can improve arsenate (As^{+5}) removal in the same way as adding polymer. The resulting settled water has lower turbidities and higher arsenic removal percentages; however, the filtered water values for both turbidities and arsenic show no significant differences in the various samples. Figures 6-17 through 6-22 show the results of several runs which had the same ferric sulfate dose and varied only in the additions of polymer, ozone, or both to the treatment process.

The importance of ozone in arsenic removal from drinking water is its ability to oxidize arsenite (As^{+3}) to arsenate (As^{+5}). The data indicate that arsenite is harder to remove from water with conventional treatment techniques than arsenate is. After preozonation, however, arsenite is converted to arsenate and can then be eliminated at the higher removal efficiency associated with water containing arsenate. Figures 6-23 and 6-24 show the results of runs made using raw water spiked with arsenite (As^{+3}) with and without preozonation. The results show a 10% to 15% increase in removal of total arsenic from the filtered water and an even greater difference in the settled water values.

6.5 RAW WATER WITH HIGH BACKGROUND LEVELS OF ARSENIC

This study utilized AS(V)- and As(III)-spiked raw water samples. Spiking of the water samples with arsenic was necessary due to very low natural background of arsenic in the raw water source. The following discussion is devoted to projecting the results of situations where natural water had an elevated level of arsenic and spiking was not required.

Natural waters with high arsenic level will have arsenic in equilibrium with other chemical constitutes. In this study, a highly soluble species of arsenic was used to reach such equilibrium in a short time. The treatability results are clearly valid if the equilibrium had reached within the available time in the overhead tank, contact chamber, and pipelines. Validation of results is only possible if the experimental program was conducted with natural water having a elevated arsenic levels. This was not possible unless a water sample with high natural arsenic source content were brought to the RHWTP for experimental purposes.

Most arsenic treatability studies conducted nationally utilized the arsenic-spiking method due to a low background arsenic level (Cheng et al. 1994; Elson et al. 1980; and Hering et al. 1996). The assumption in all cases is that arsenic treatability results are applicable to natural waters with elevated arsenic levels.

The investigation conducted in this study provides a treatability trend that can be fully utilized to real situations. Perhaps a research program similar to this shoujld be conducted on water samples that have an elevated natural arsenic background. The actual data can be compared with the results and validated.

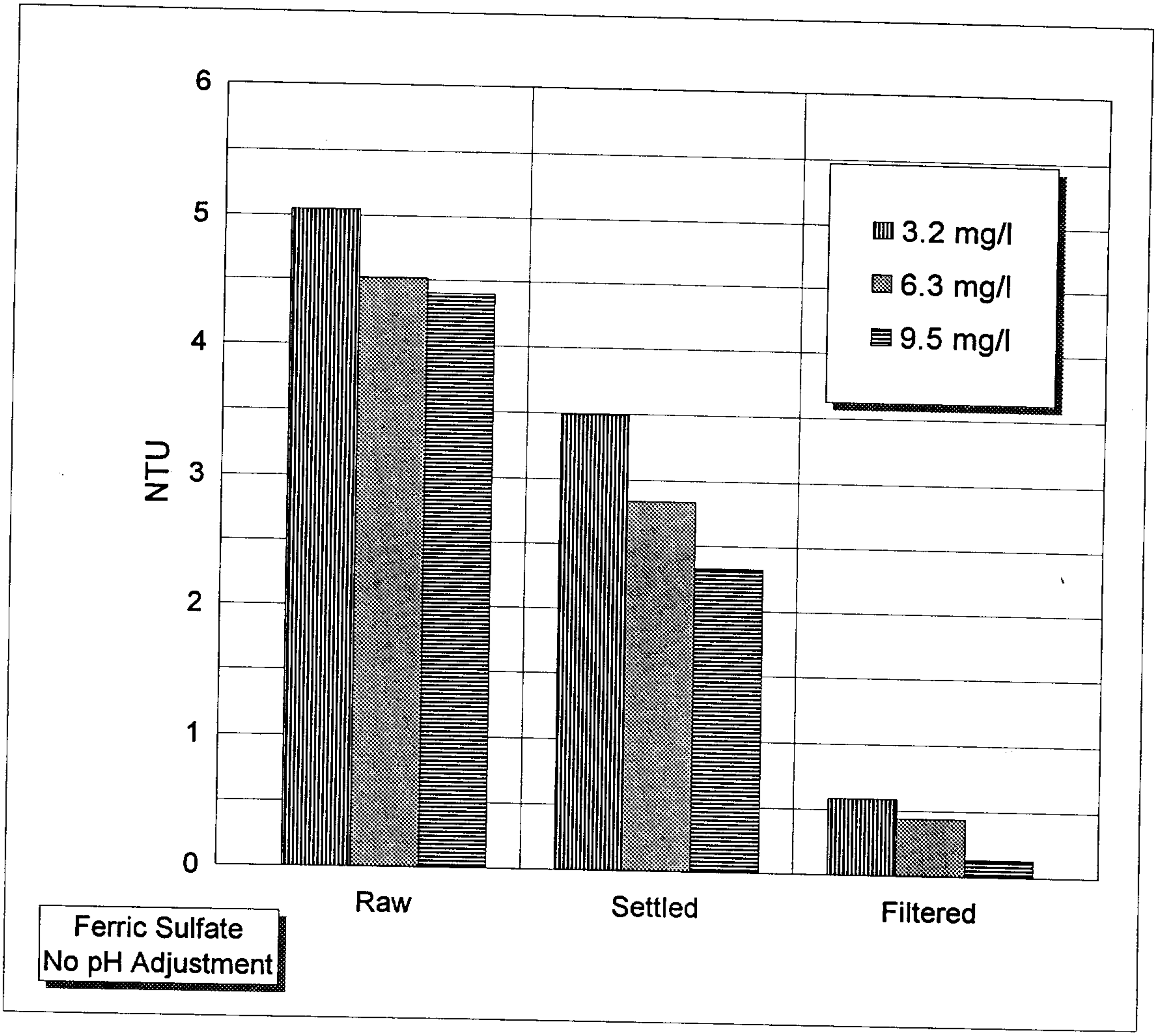


FIGURE 6-2
Turbidity Removal for Varying Coagulant Doses

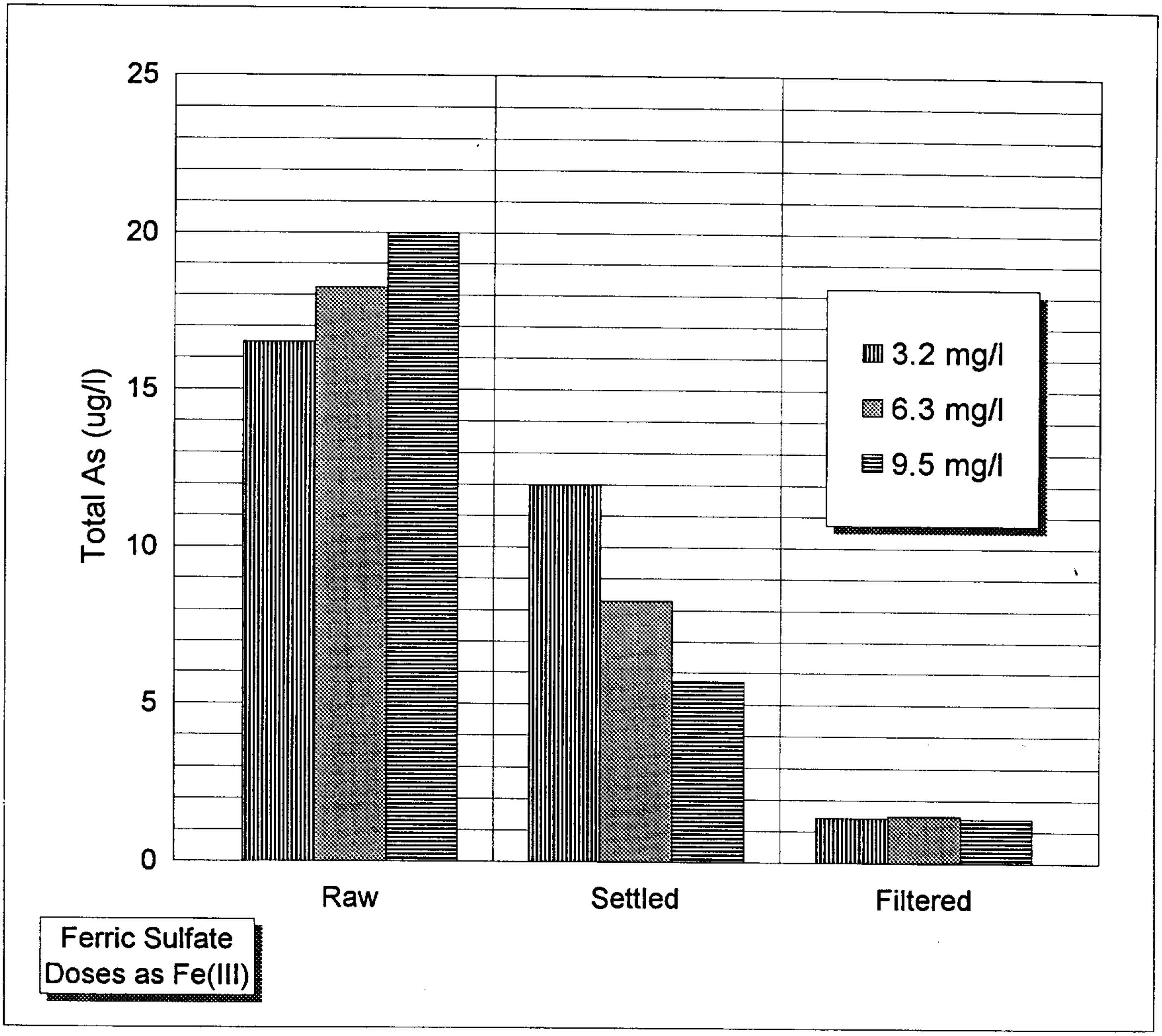


FIGURE 6-3
Total Arsenic Removal for Varying Coagulant Doses

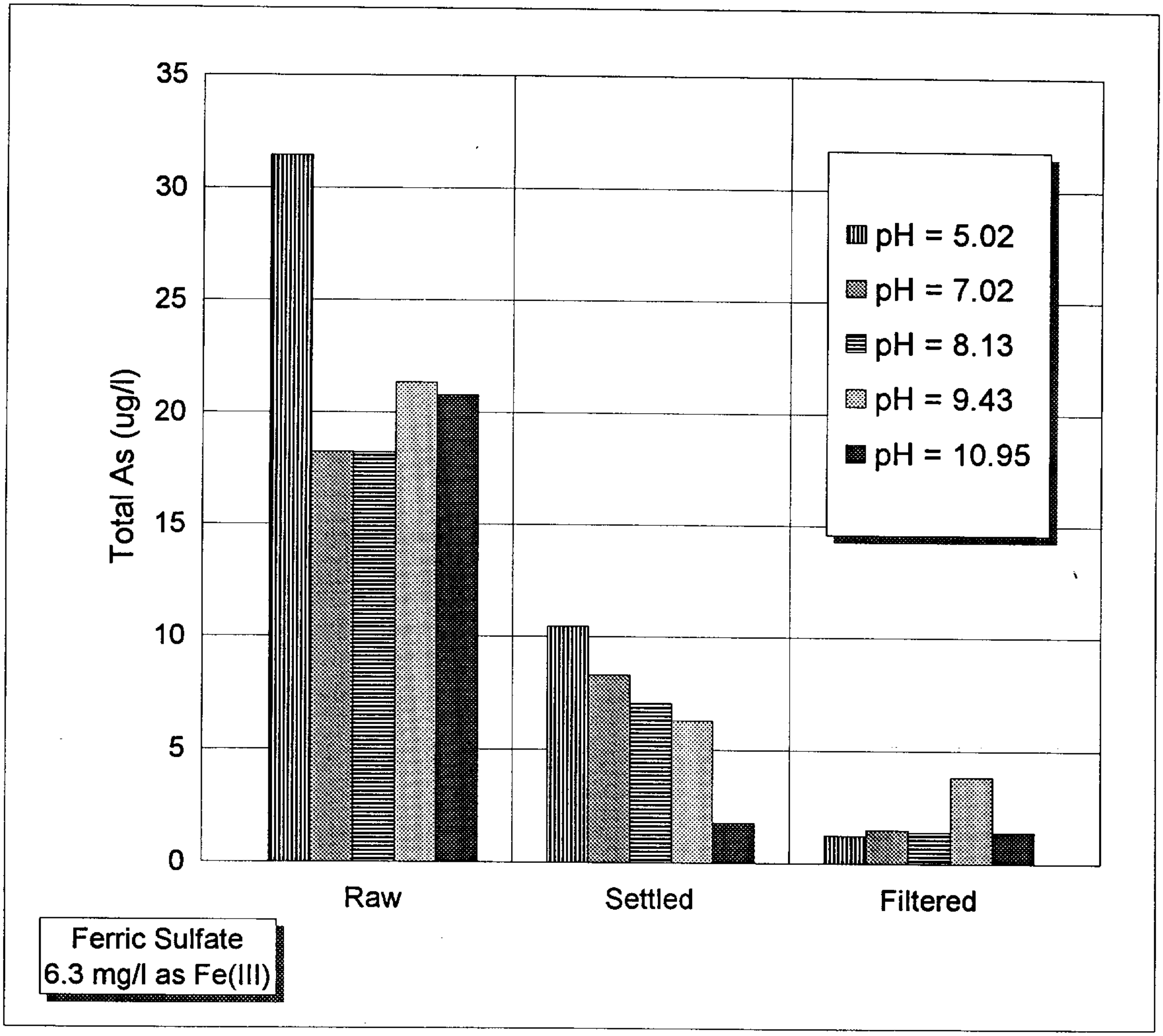


FIGURE 6-4
Total Arsenic Removal for Varying pH

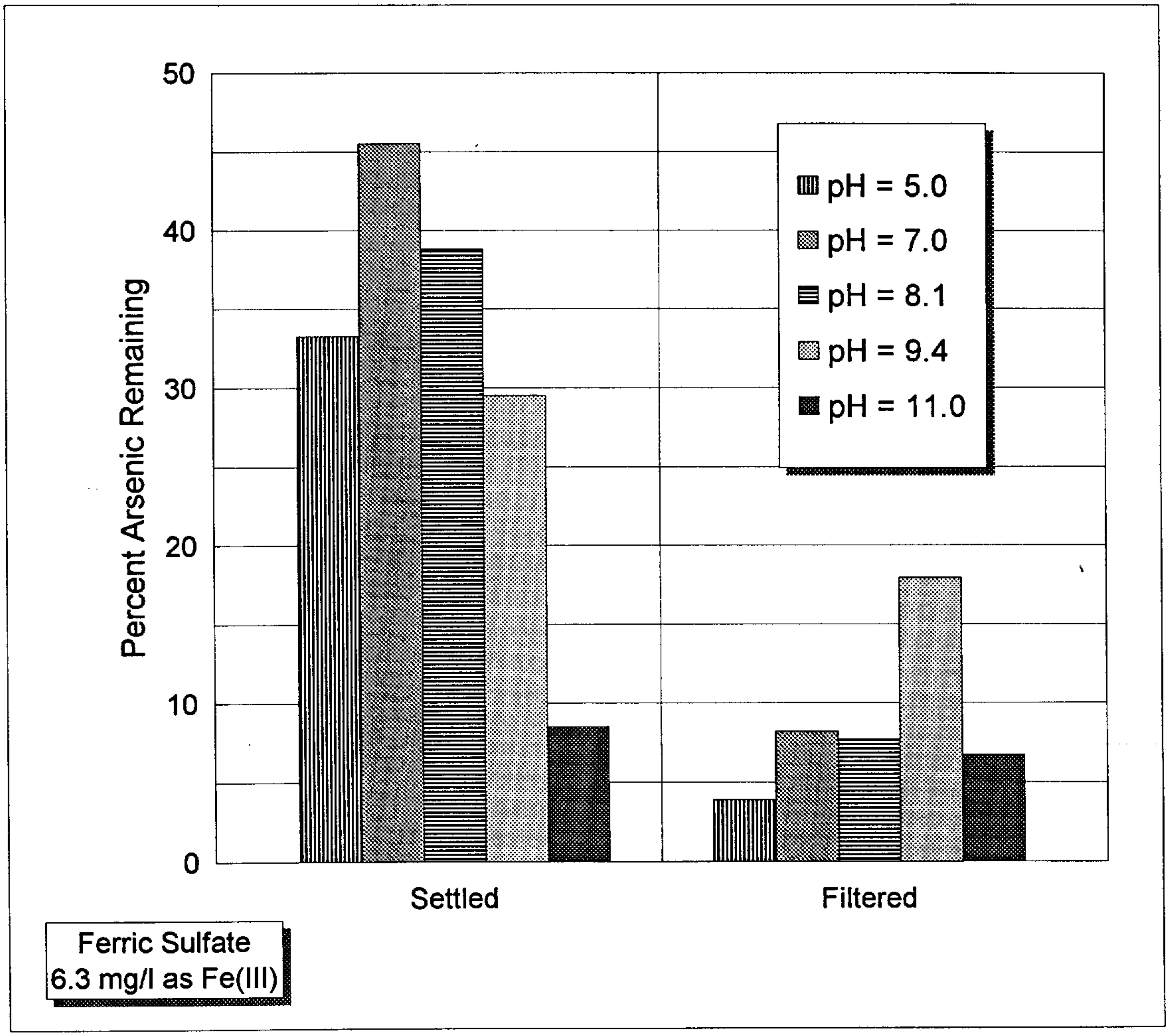


FIGURE 6-5

Total Arsenic Removal as Percentage of Initial Concentration
In Raw Water under Different Final pH Conditions

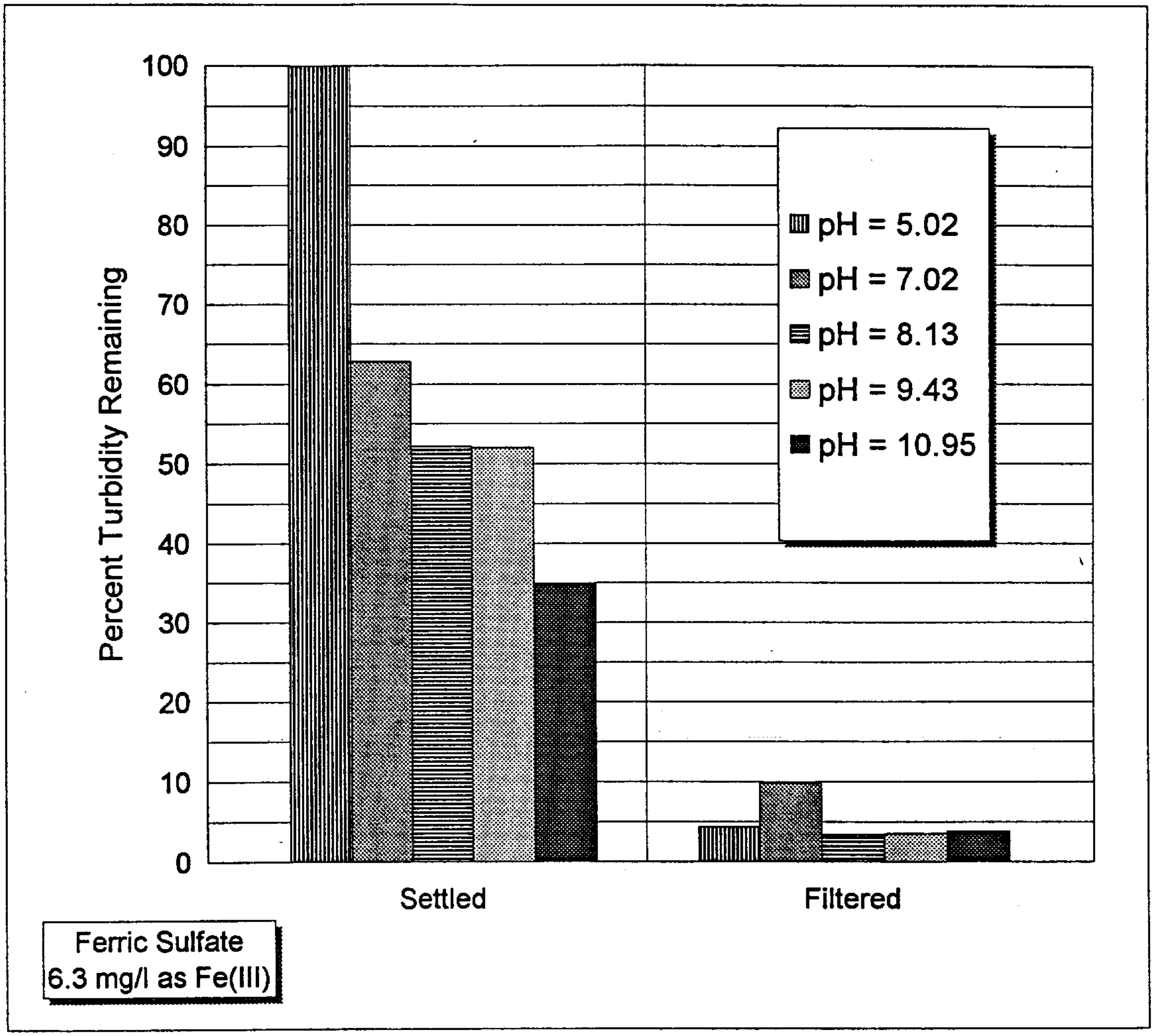


FIGURE 6-6

Percent Turbidity Remaining as Percentage of Initial
Level in Raw Water under Different pH Conditions

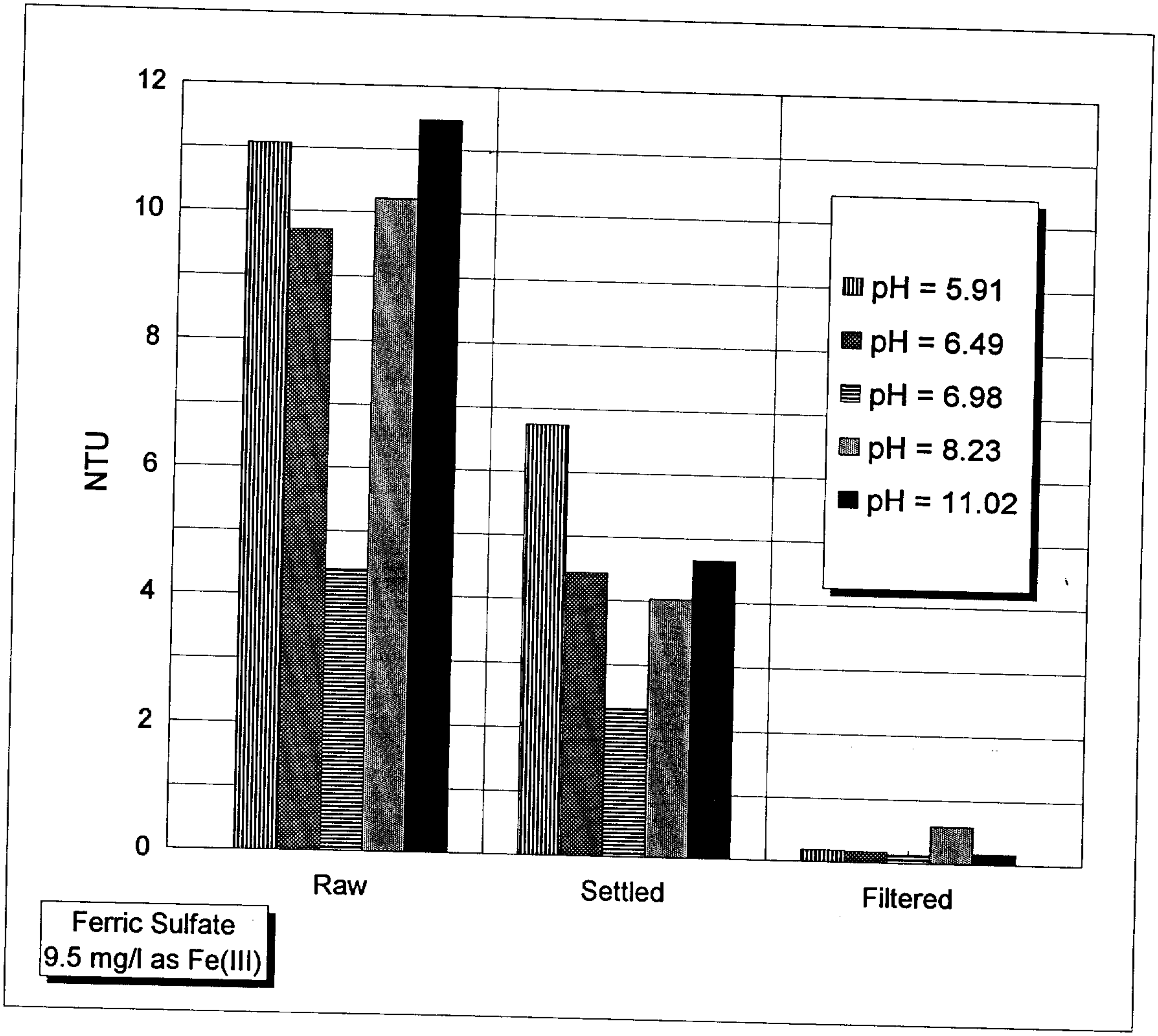


FIGURE 6-7
Turbidity Removal for Varying pH - High Coagulant Dose

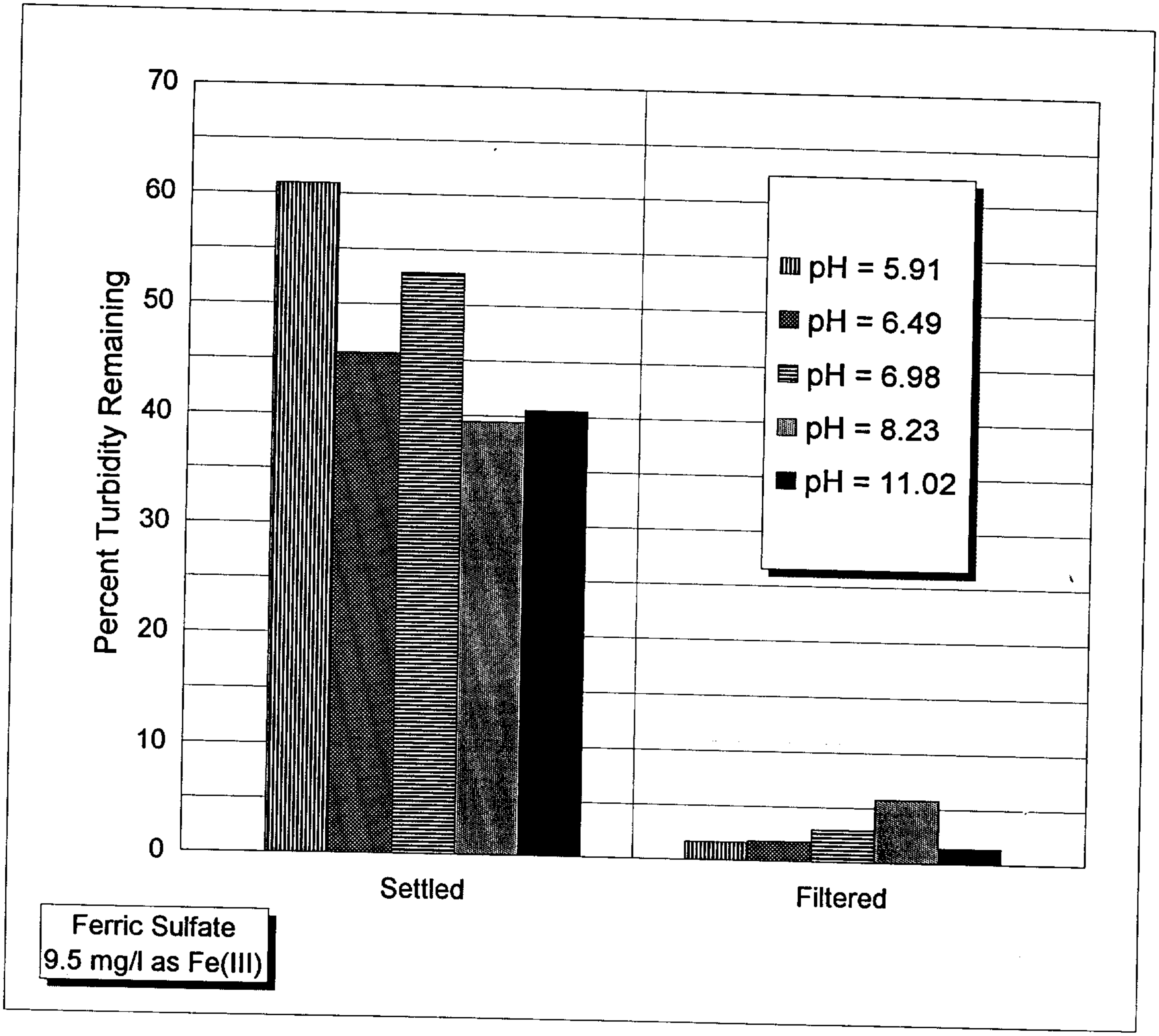


FIGURE 6-8
Percent Turbidity Removal for Varying pH - High Coagulant Dose

Note: 1 mg/l was the TOC detection limit

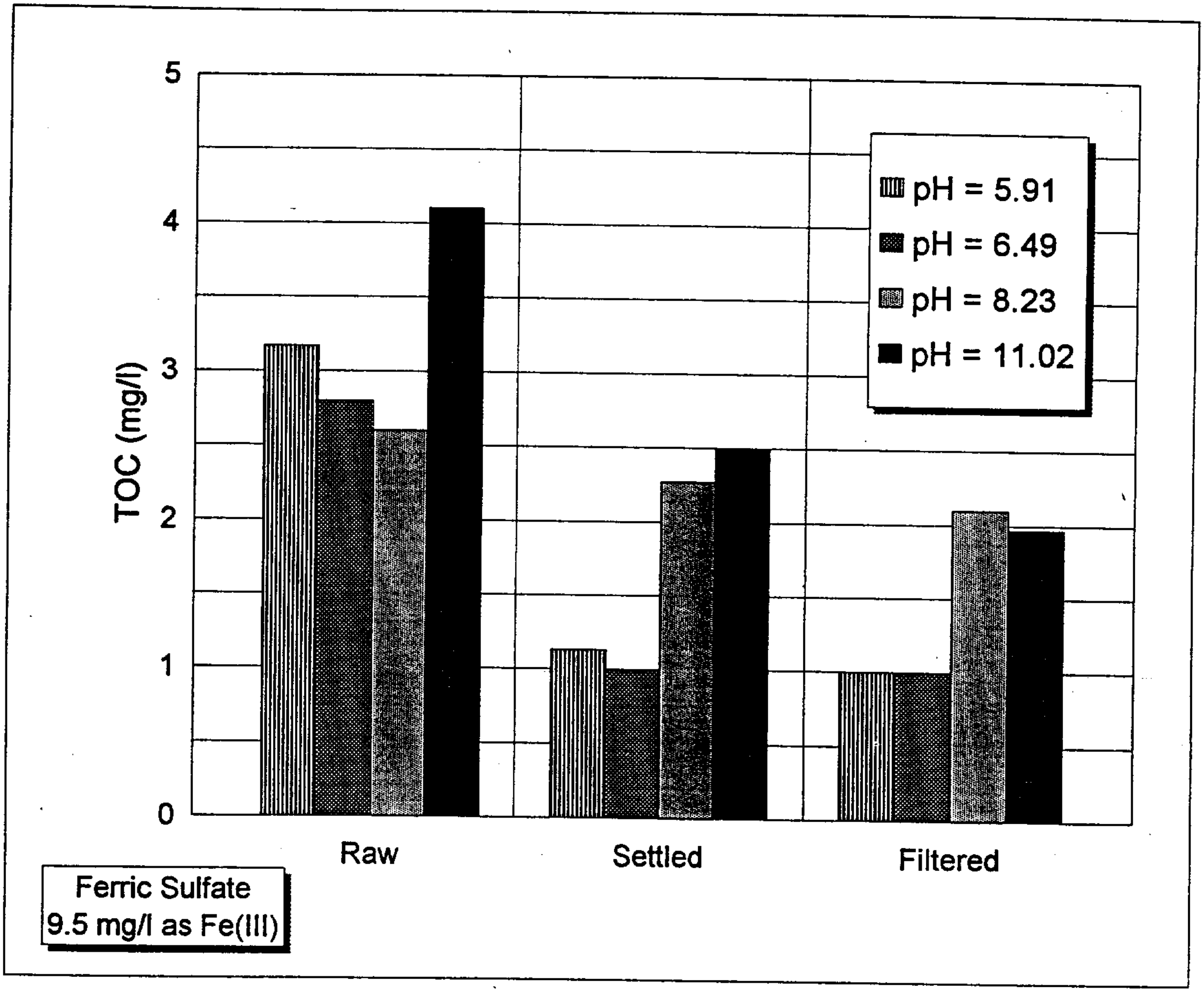


FIGURE 6-9

TOC Removal for Varying pH - High Coagulant Dose

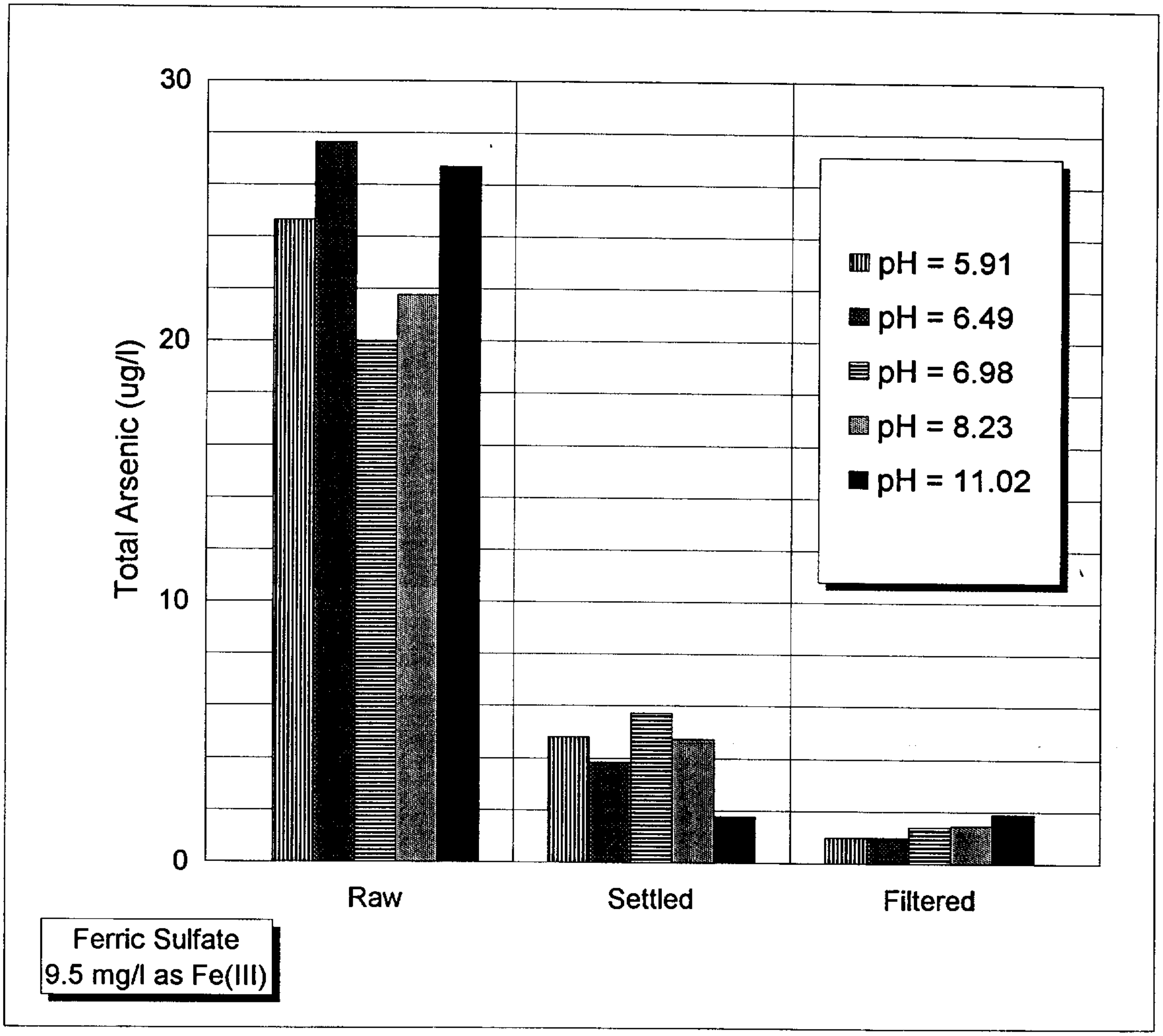


FIGURE 6-10
Total Arsenic Removal for Varying pH - High Coagulant Dose

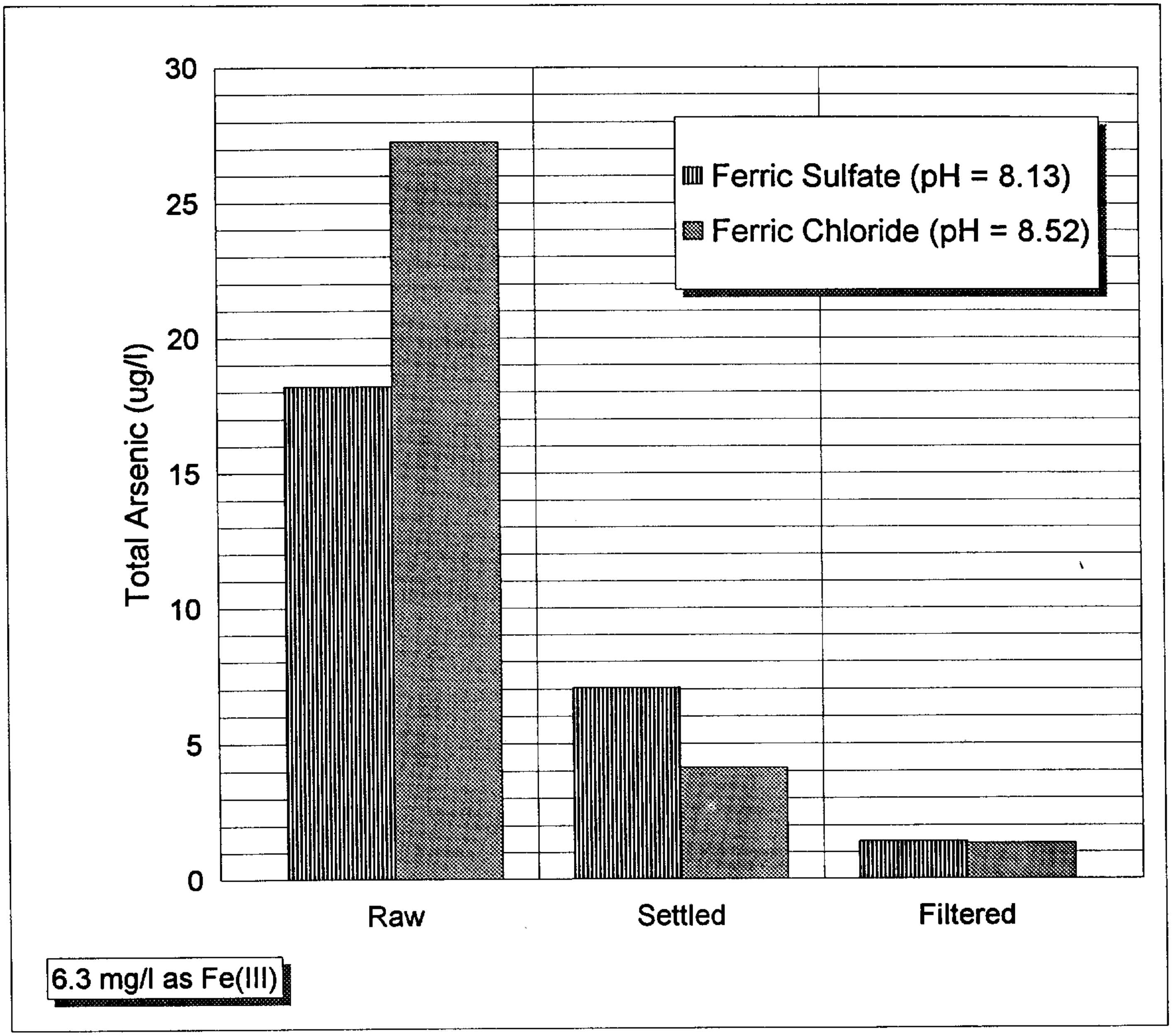


FIGURE 6-11
Total Arsenic Removal - Ferric Sulfate vs Ferric Chloride

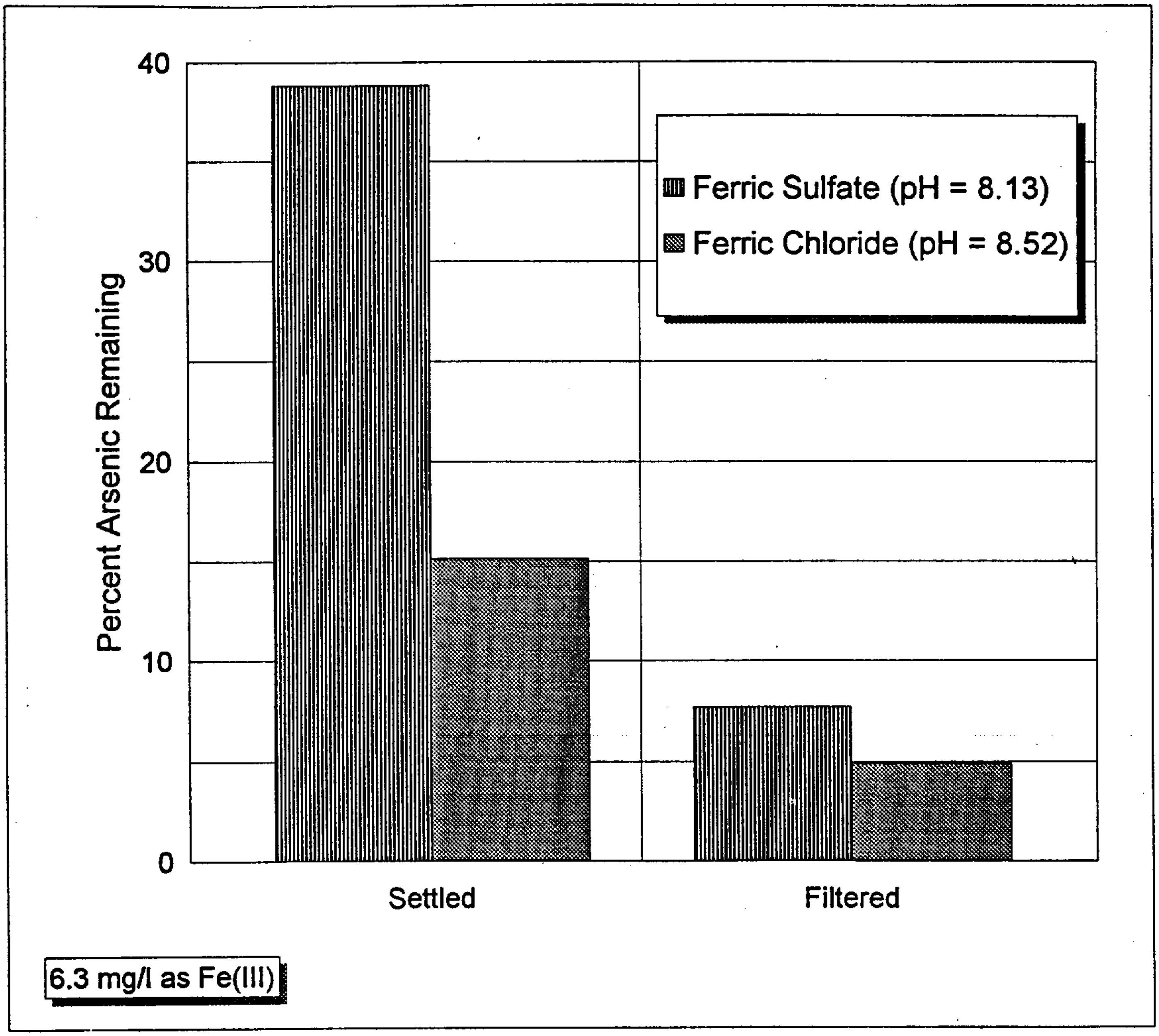


FIGURE 6-12

Total Arsenic Remaining as Percentage of Initial Concentration in Raw Water
- Ferric Sulfate vs Ferric Chloride

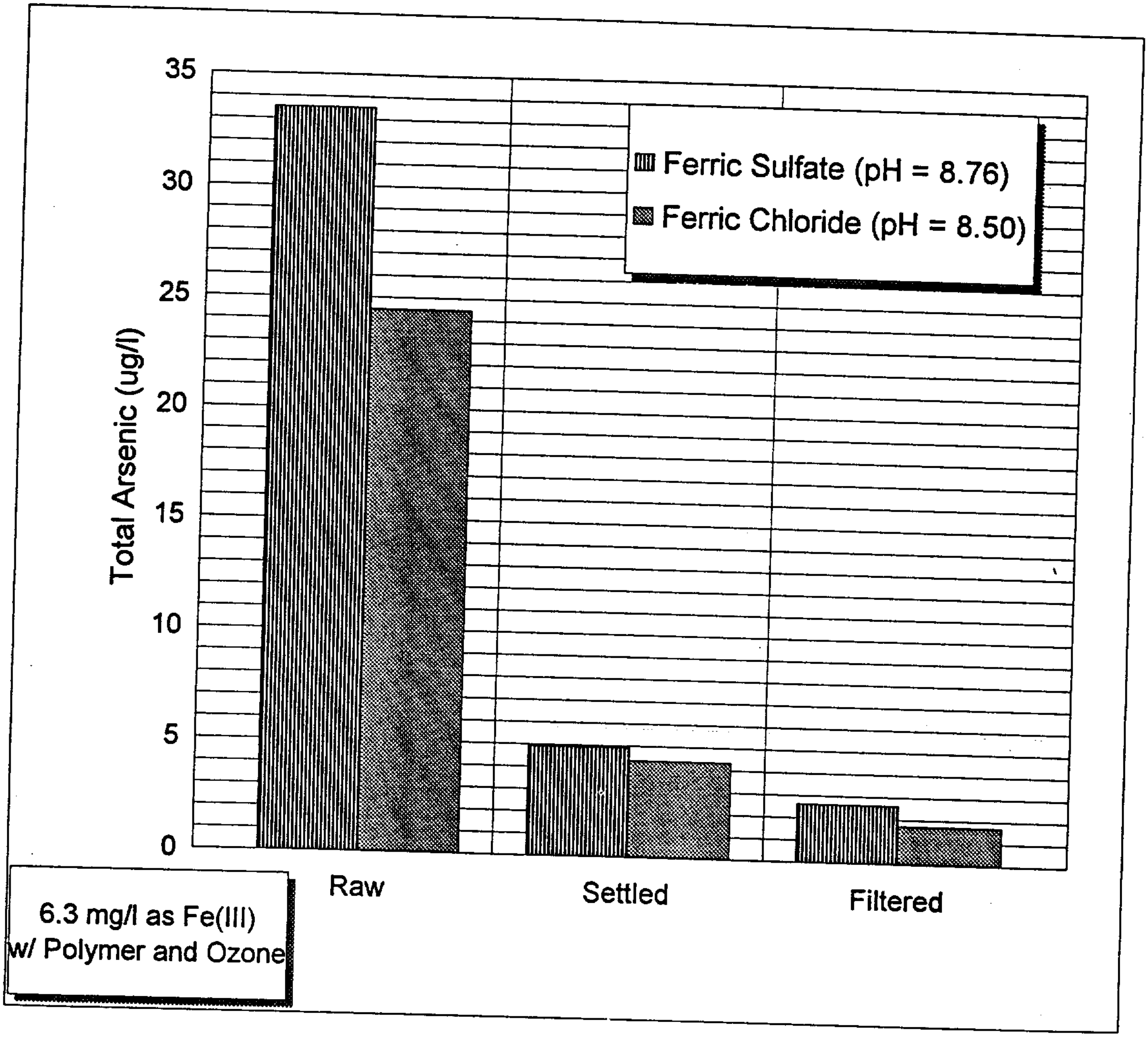


FIGURE 6-13

Total Arsenic Removal - Ferric Sulfate vs Ferric Chloride
- Polymer and Ozone Added

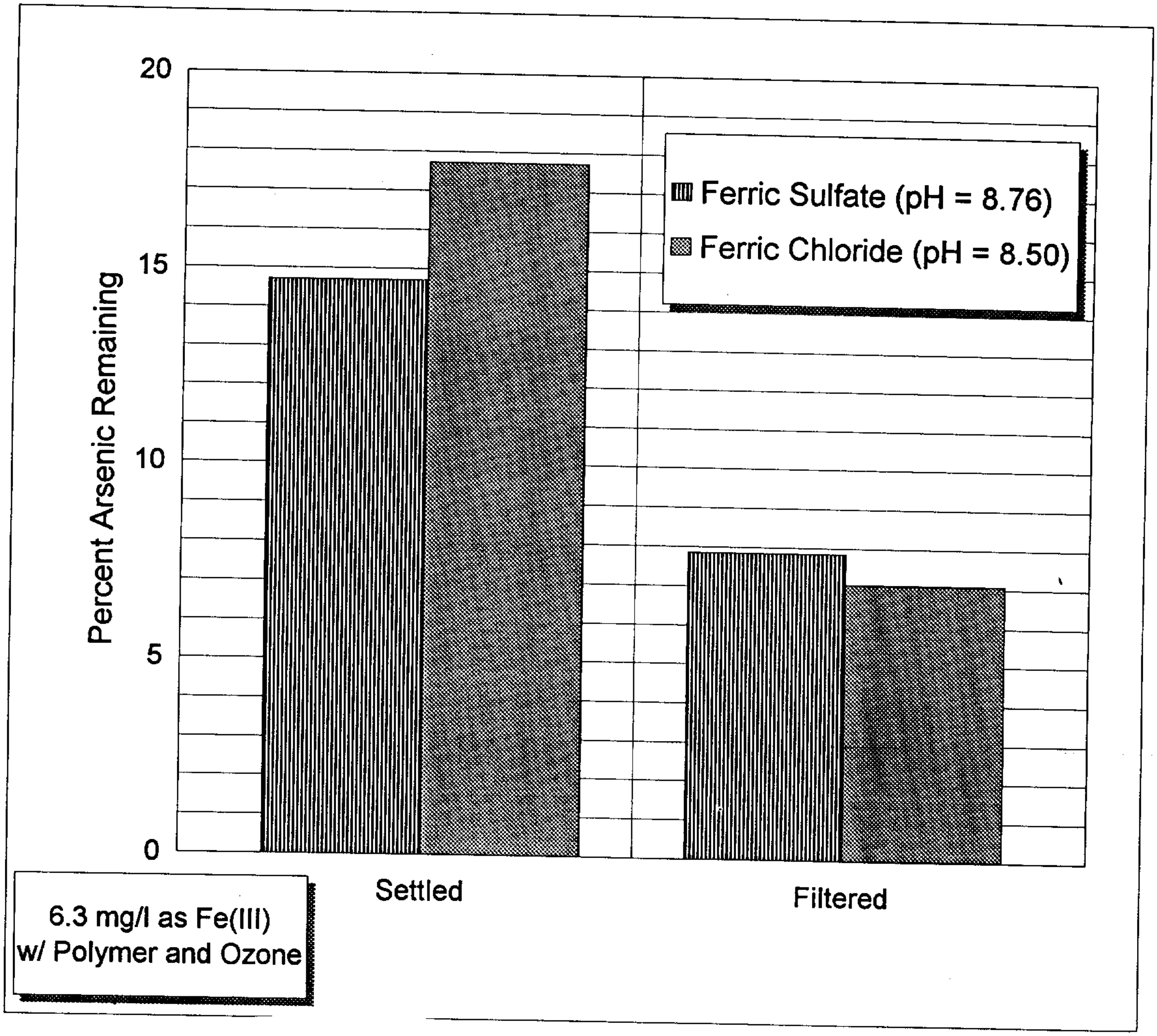


FIGURE 6-14

Total Arsenic Remaining as Percentage of Initial Concentration in Raw Water
- Ferric Sulfate vs Ferric Chloride
- Polymer and Ozone Added

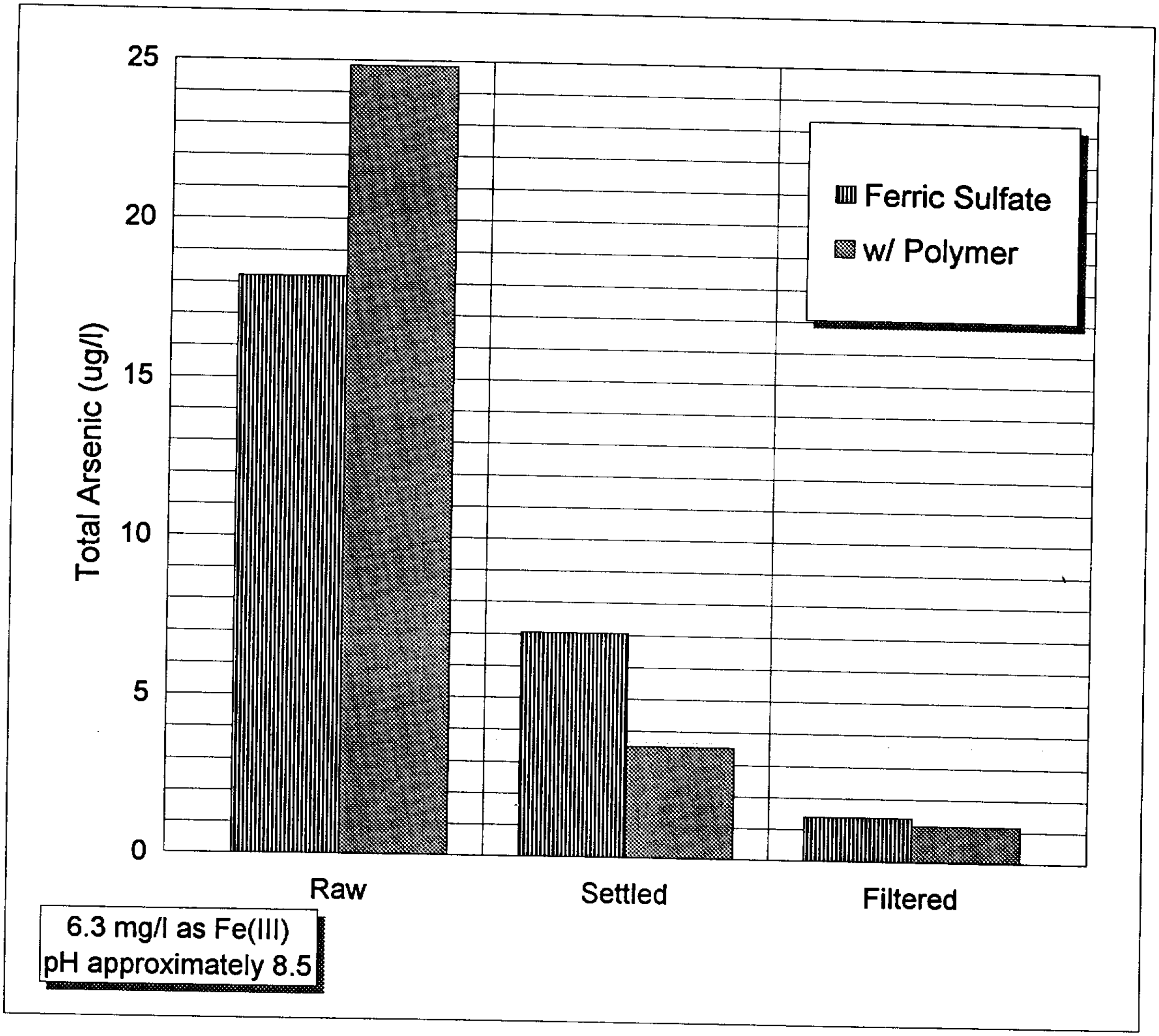


FIGURE 6-15
Polymer Effects on Total Arsenic Removal

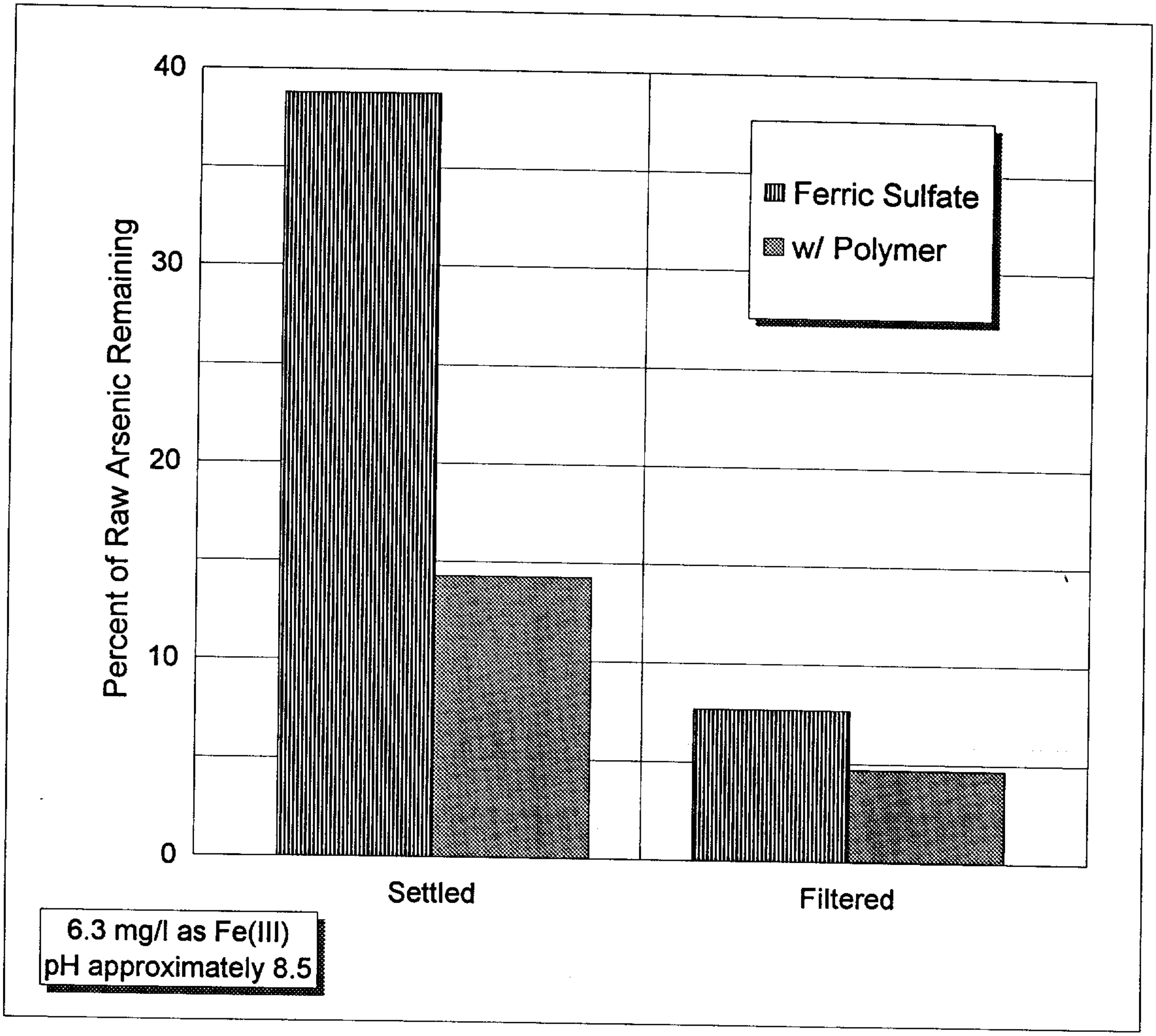


FIGURE 6-16
Polymer Effects - Percentage of Raw Arsenic Remaining

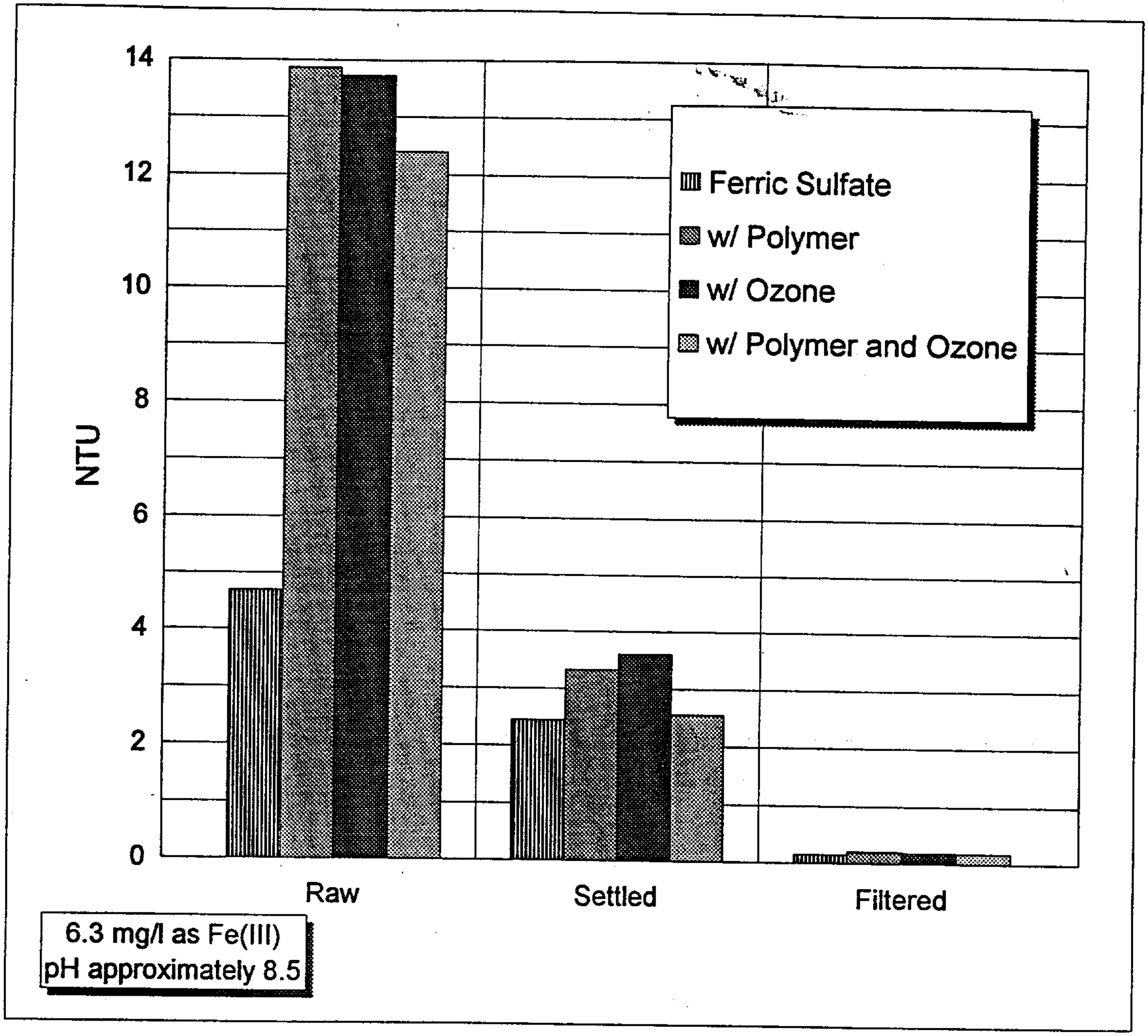


FIGURE 6-17

Comparison of Turbidity Removal under Different Operational Conditions

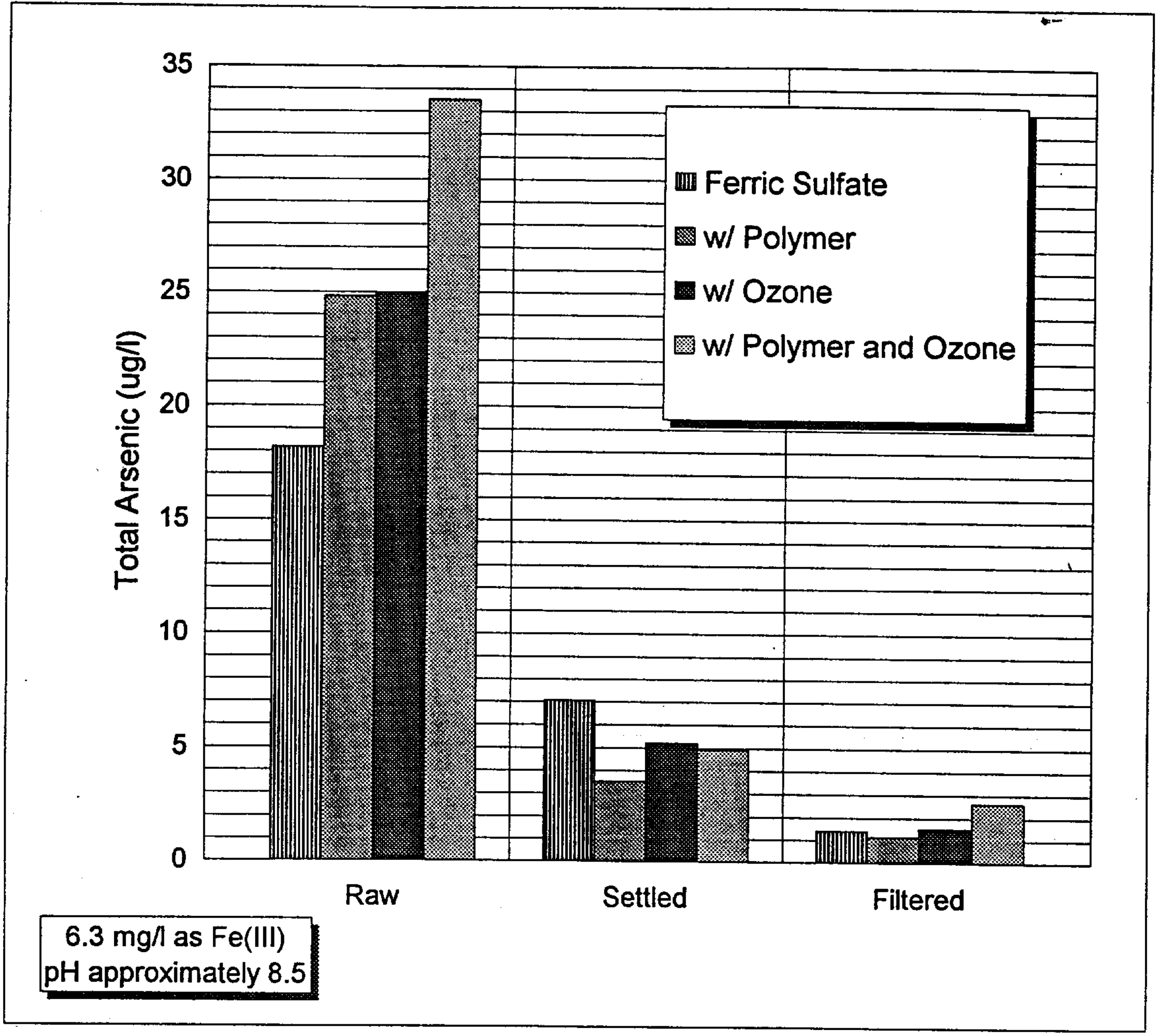


FIGURE 6-18

Comparison of Total Arsenic Removal under Different Operational Conditions

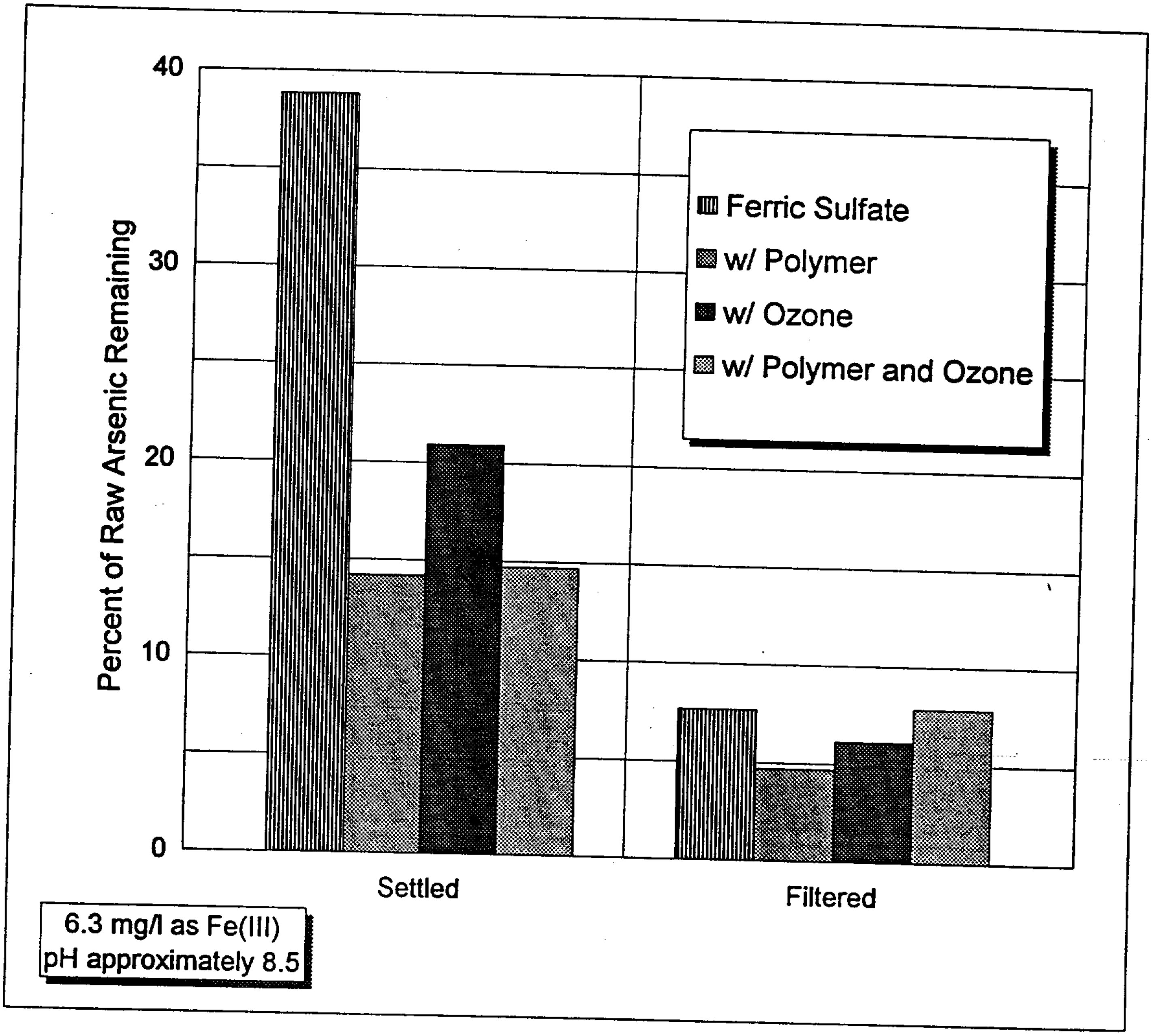


FIGURE 6-19

Comparison of Total Arsenic Remaining as Percentage of Initial Concentration in Raw Water under Different Operational Conditions

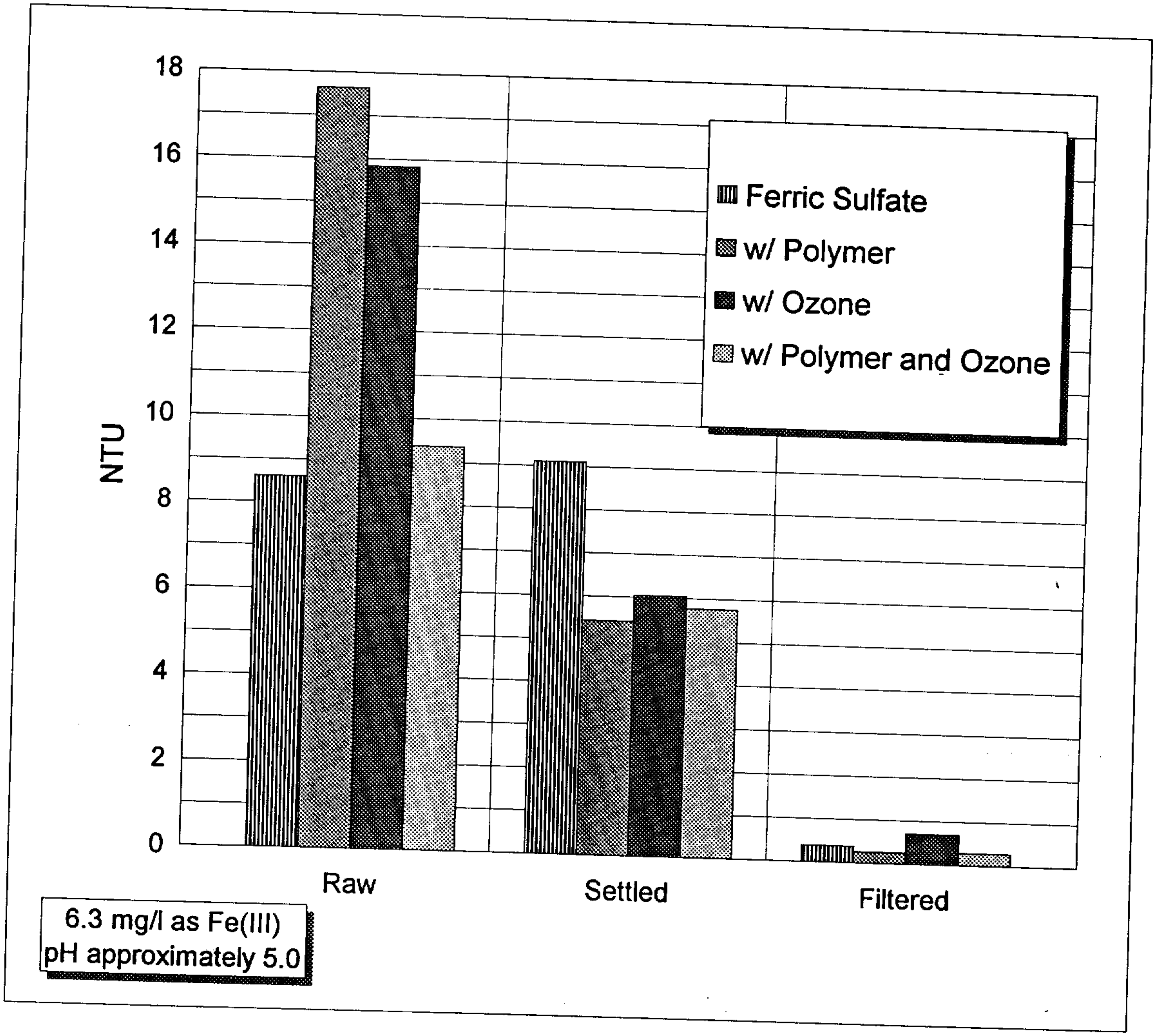


FIGURE 6-20

Comparison of Turbidity Removal at Low pH Levels under Different Operational Conditions

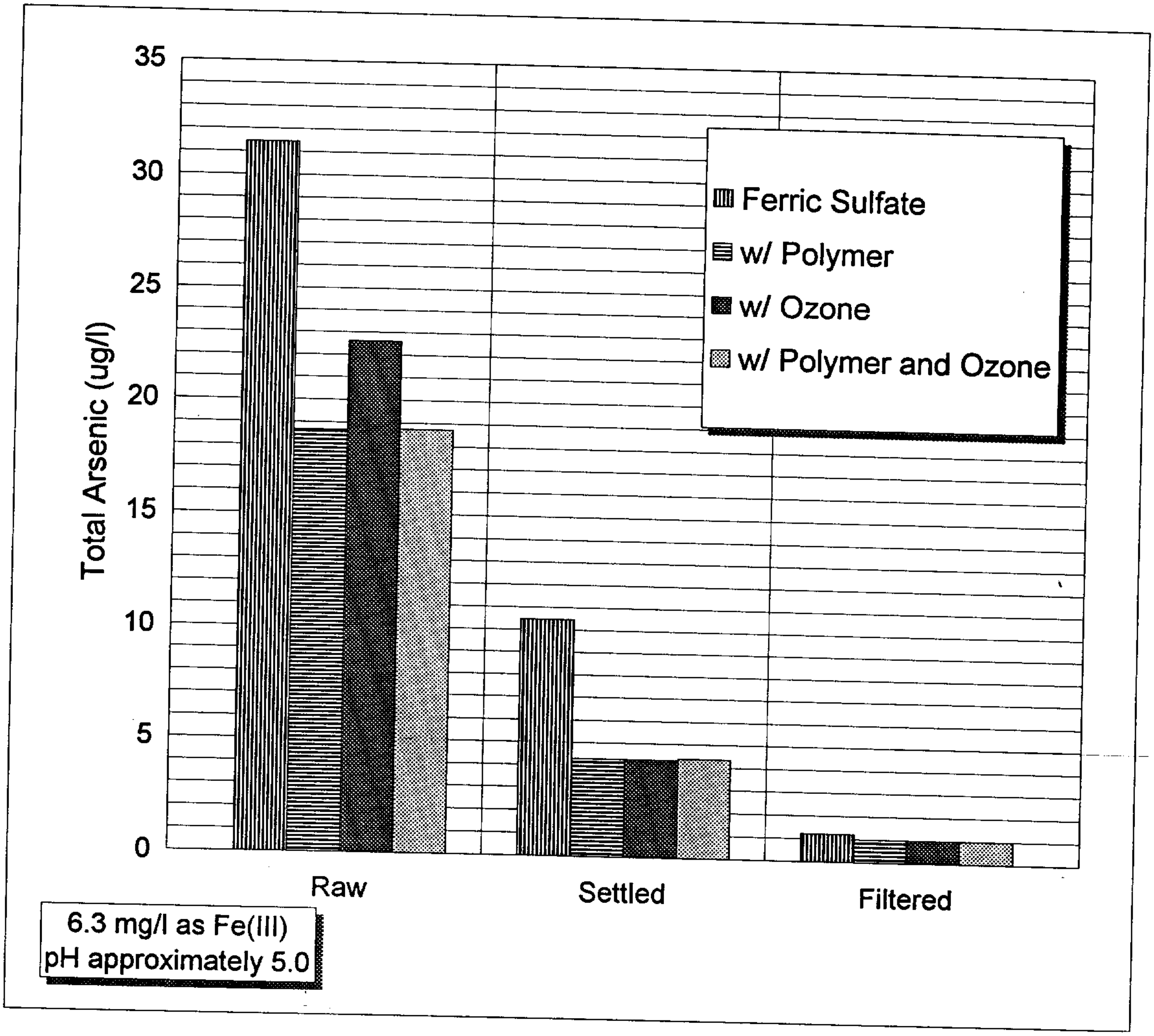


FIGURE 6-21

Comparison of Total Arsenic Removal at Low pH Levels
under Different Operational Conditions

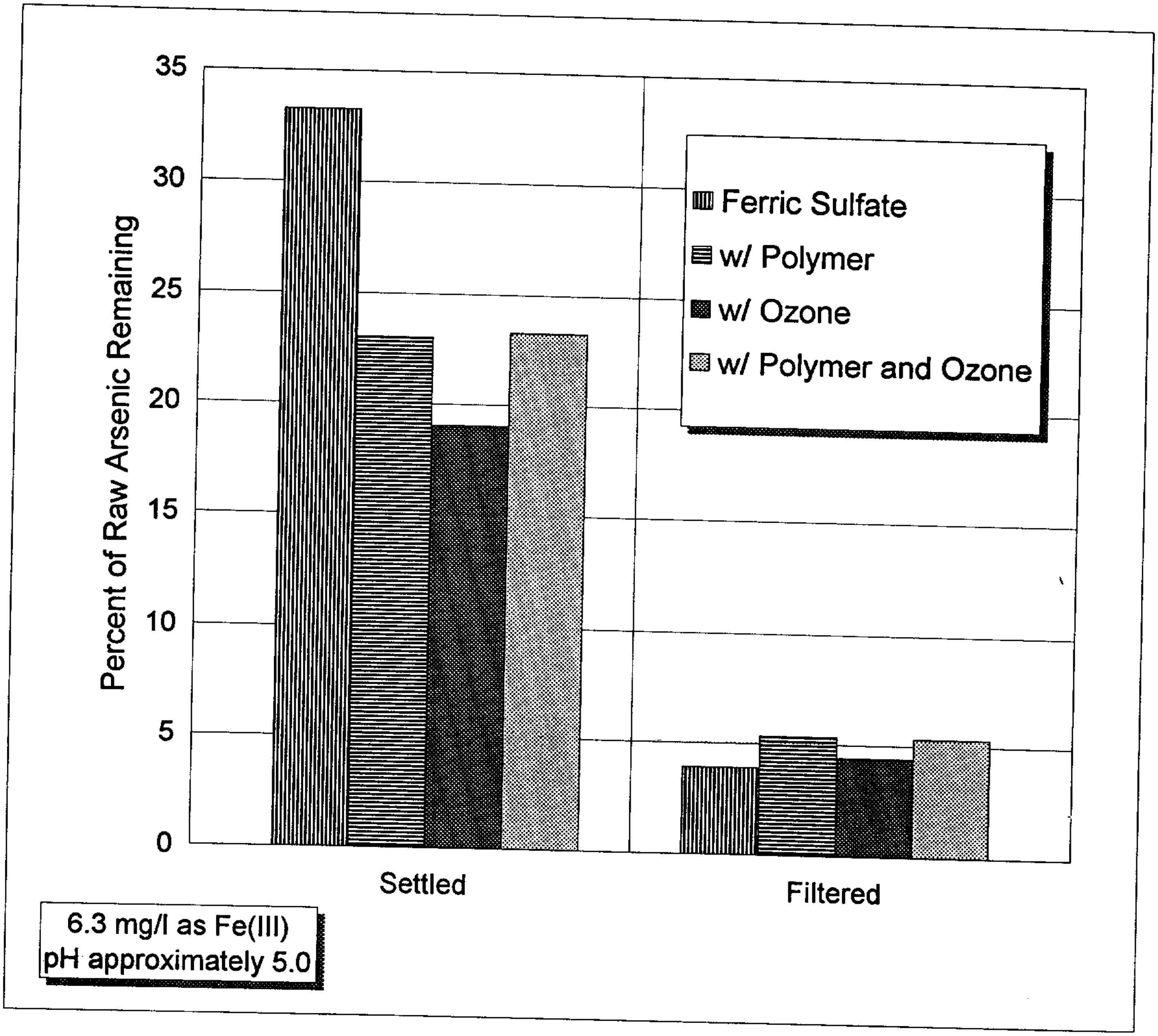


FIGURE 6-22

Comparison of Total Arsenic as Percentage of Initial Concentration in Raw Water at Low pH Levels under Different Operational Conditions

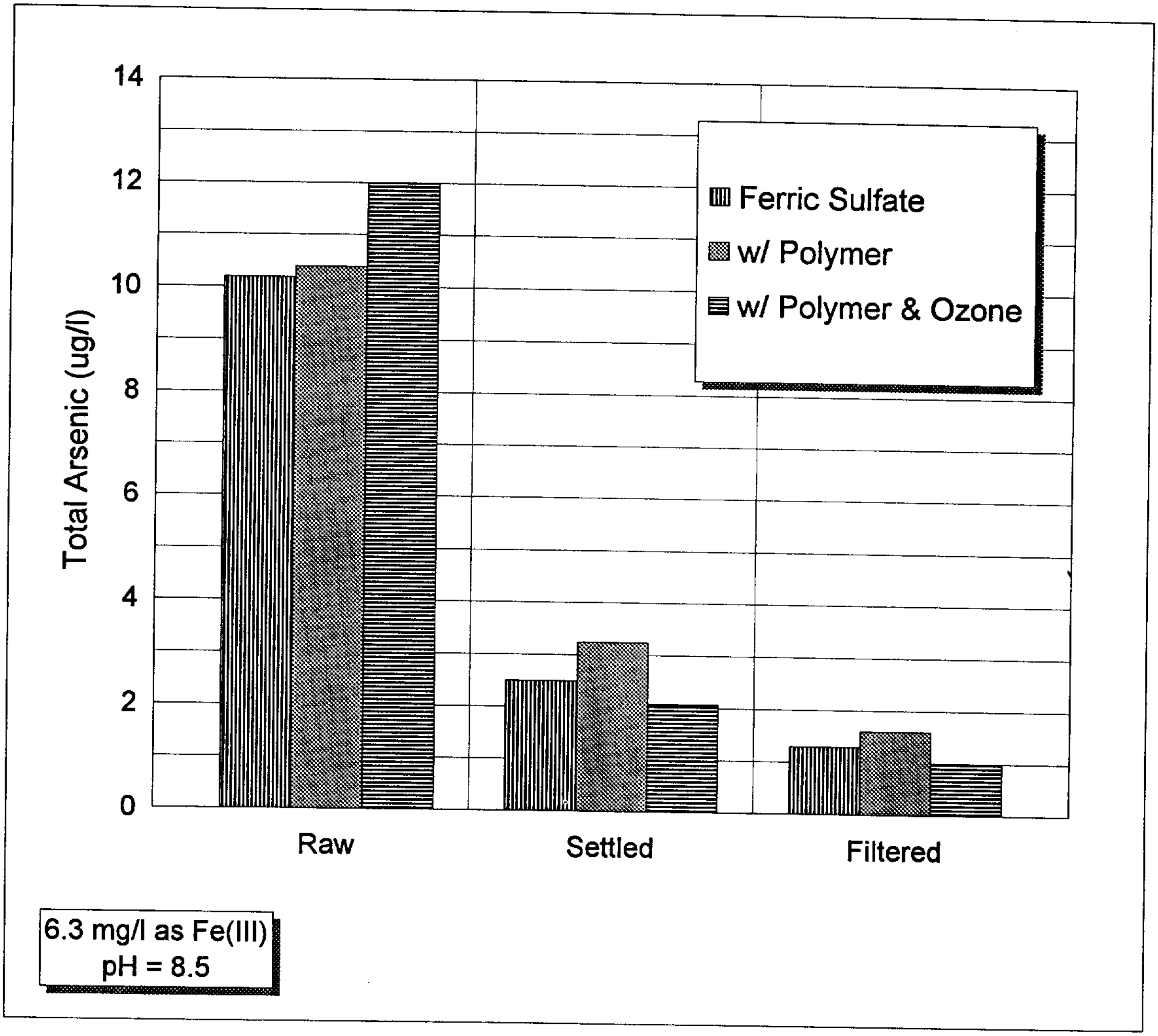


FIGURE 6-23

Arsenite [As(III)] Remaining with Ferric Sulfate
under Different Operational Conditions

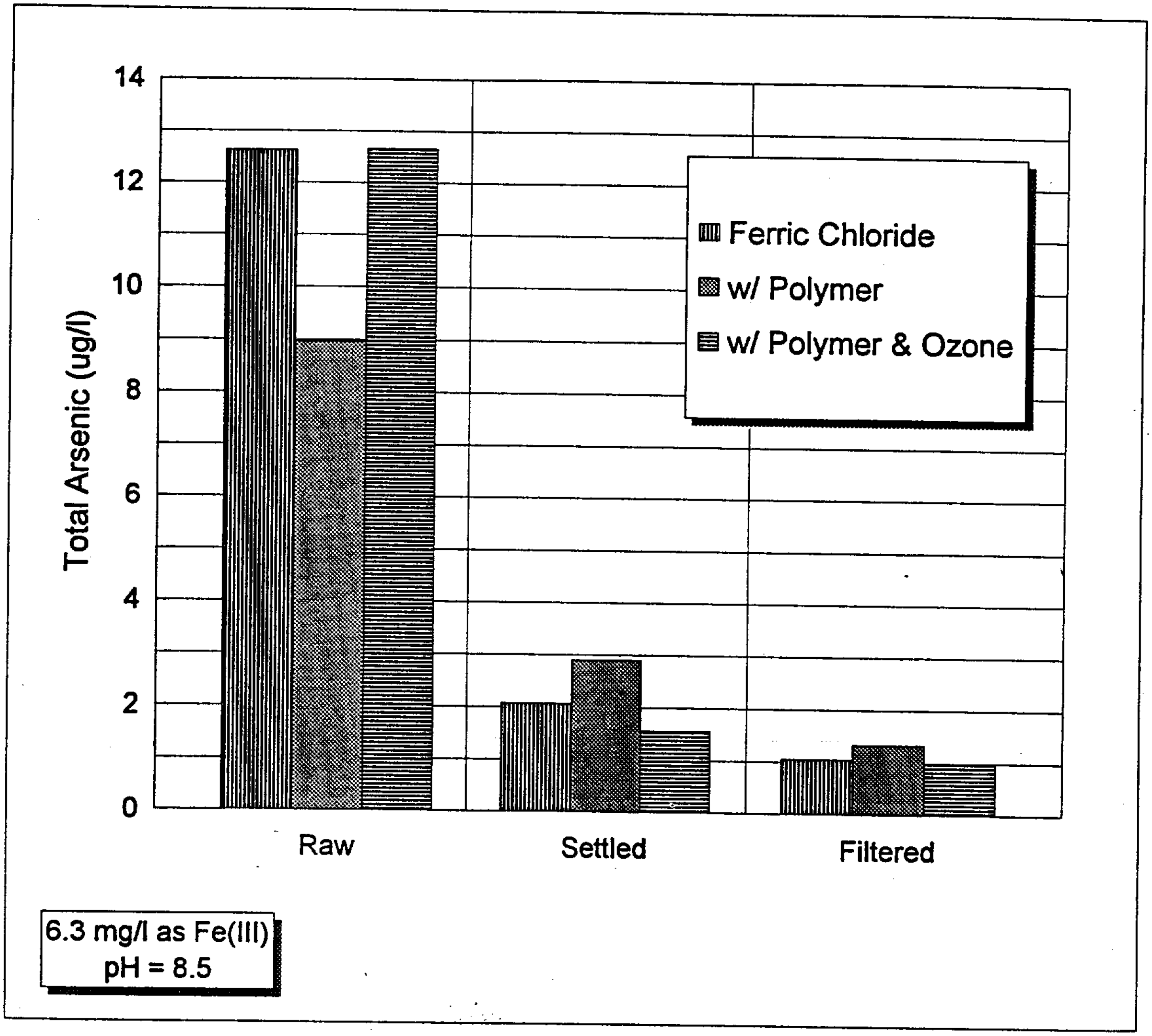


FIGURE 6-24

Arsenite [As(III)] Removal with Ferric Chloride under Different Operational Conditions

Chapter 7

PROJECTED ENERGY CONSUMPTION DUE TO INCREASED OZONATION PRACTICE IN MUNICIPAL WATER TREATMENT

Ozonation in drinking water treatment practice is gaining interest across North America. The primary objectives of ozonation are (1) enhanced disinfection and control of D-DBPs, (2) destruction of by-products of ozonation in biologically active carbon or filter beds, and (3) general improvement in the aesthetic quality of, for example, taste, odor, and color. This section of the report addresses the very vital issue of energy demand nationwide as more and more water utilities utilize ozonation in water treatment.

7.1 OZONATION PRACTICE

7.1.1 CHEMISTRY

Ozone is a powerful oxidizing agent and thus a powerful disinfectant. When exposed to a neutral or alkaline environment (pH above 6), UV light, or hydrogen peroxide, it decomposes in water to product more active hydroxyl radicals. The hydroxyl radical (OH), or a mixture of ozone and the hydroxyl radical, is a powerful oxidizing agent which reacts with NOM, producing lower molecular organic species. Among these are aldehydes, ketones, and acids. Ozone does not produce halogenated organic matter directly. However, in the presence of bromide ion, hydrobromic acid is formed, perhaps encouraging formation of brominated organics.

7.1.2 METHODS OF OZONE GENERATION

Ozone may be generated from air or oxygen. Feed air to an ozone generator must be dried to a maximum dew point of -65° C. Moisture in air reduces ozone production, causes fouling of dielectric tubes, and increases corrosion in ozone generators and downstream equipment.

Ambient air feed systems for ozone generation have a low, medium, or high operating pressure. Low-pressure systems operate in a partial vacuum created by a submerged turbine or other ejector devices. Medium-pressure systems range from 0.7 to 1.05 kg/m^2 (10 to 15 psig). High-pressure systems operate at pressures ranging from 4.9 to 7.03 kg/cm^2 (70 to 100 psig) and reduce the pressure prior to ozone generator. Pressure desiccant dryers are also used in conjunction with compression and refrigerant dryers to generating large and moderate quantities of ozone. Very small systems use two desiccant dryers (no compression or refrigerant drying). Desiccant dryers use silica gel, activated alumina, or molecular sieves to dry air to the necessary dew point.

Feed gas can also be pure oxygen. Basic features of air feed and pure oxygen feed systems are given below. The many benefits of oxygen-generating systems over air feed are (1) higher production density (more ozone produced per unit area of the dielectric), (2) high concentration of ozone in the product gas (almost double), (3) lower energy requirements, (4) smaller feed gas volume for the same ozone output, and (5) less need for ancillary equipment. For small to medium-size systems, oxygen may be purchased as a gas or as a liquid. For large operations, oxygen generation on site may be necessary. There are two methods of producing oxygen on site for ozone generation: (1) pressure swing adsorption of oxygen from air and (2) cryogenic production (liquefication of air followed by fractional distillative separation of oxygen from nitrogen). Systems for production of oxygen on site contain many of the same elements as the air preparation system, since the feed gas must be clean and dry, irrespective of the oxygen content.

The voltage or frequency of the power to the ozone generation must be varied to control the amount and rate of the ozone produced. Ozone generators use high voltages (710,000) or high-frequency electrical current (up to 2,000 Hz); therefore, specialized power supply equipment and design considerations, such as proper insulation or wiring and cooling of transformers, are necessary.

Ozone can be generated by two methods: (1) UV light and (2) cold plasma or corona discharge. Ozone is generated by UV light in the same way as ozone is formed in the upper atmosphere. UV light (less than 200 nm) is produced by an arc discharge lamp and passes through dry or oxygenenriched air. Ozone is generated by photochemical reaction. Ozone generated by this method is much lower in concentration (0.25 percent) than that produced by corona discharge. This method is suited only for small-scale systems, requires low capital investment, and is relatively easy to maintain.

The most common method used to generate ozone for water treatment is the corona discharge cell. The discharge cell consists of two electrodes separated by a discharge gap. High voltage potential is maintained across a dielectric material, and feed gas flows between the electrodes. Ozone concentration of 1 to 3.5 percent by weight is generated from cool and dry feed air, and 2 to 7 percent from pure oxygen.

The most common commercially available ozone generators are horizontal or vertical tubes or plates with a water-, air-, or oil-cooled system. These are the operating conditions for these generators:

- Low frequency (60 Hz), high voltage (>20,000V)
- Medium frequency (<1,000 Hz), medium voltage (10,000 - 20,000)
- High frequency (>1,000 Hz), low voltage (<10,000V)

Currently, low-frequency, high-voltage units are most common, but recent improvements in electronic circuitry make higher-frequency, low-voltage units more desirable. Ozone generation at 60 to 70 percent of maximum generation capacity is most cost-effective. Multiple units, if selected properly, should satisfy average and peak demands and provide necessary standby units for maintenance.

7.1.3 GROWTH OF MUNICIPAL WATER TREATMENT FACILITIES USING OZONATION IN THE UNITED STATES

The number of ozonation facilities at municipal water treatment plants increased from fewer than 10 in 1980 to more than 100 in 1994. Forty more ozone systems are projected to be on line by

1998. Half of the ozone systems in operation are plants that produce less than 10 mgd. However, the majority of new systems planned are at plants larger than 10 mgd. The growth of ozone application in water treatment may be judged by the number of plants using ozone. Rakness and Counters (1996) gave a projection of the number of plants using ozonation. Figure 7-1 shows the number of plants using ozone from 1980 to 1998.

7.1.4 FACTORS AFFECTING COST OF OZONATION IN WATER TREATMENT

Ozonation increases the energy consumption at water treatment plants. The energy consumption is defined as the energy required to produce a unit mass of ozone, expressed as kWh/lb. This is also called specific energy. The overall goal of a water utility should be to produce ozone at the lowest possible specific energy. The cost of ozonation in water treatment depends upon the following factors: (1) the water quality performance ratio, (2) ozone dose and consumption, (3) specific energy, and (4) energy costs. Each of these factors is discussed below.

Water Quality Performance Ratio

The water quality performance ratio is the ratio of the applied dose and the theoretical dose needed to achieve a target result. The goal is to operate a facility at a performance ratio slightly greater than 1.0. In practice, however, the ratio may be as high as 3. This may be due to the fluctuations in the water quality, response time, precision level of necessary instrumentation, and the desired factor of safety.

Ozone Dose and Consumption

Most surface waters have an ozone demand which depends upon the water quality, temperature, and desired residual level. Ozone dose is expressed as mg/L or lb per million gallons. The goal is to optimize ozone system operation and also meet the performance ratio target at the lowest possible ozone dose. The monthly average ozone dose and ozone residual curve for Eagle Mountain Water Treatment Plant, Fort Worth, Texas, from May 1995 to April 1996 is shown in

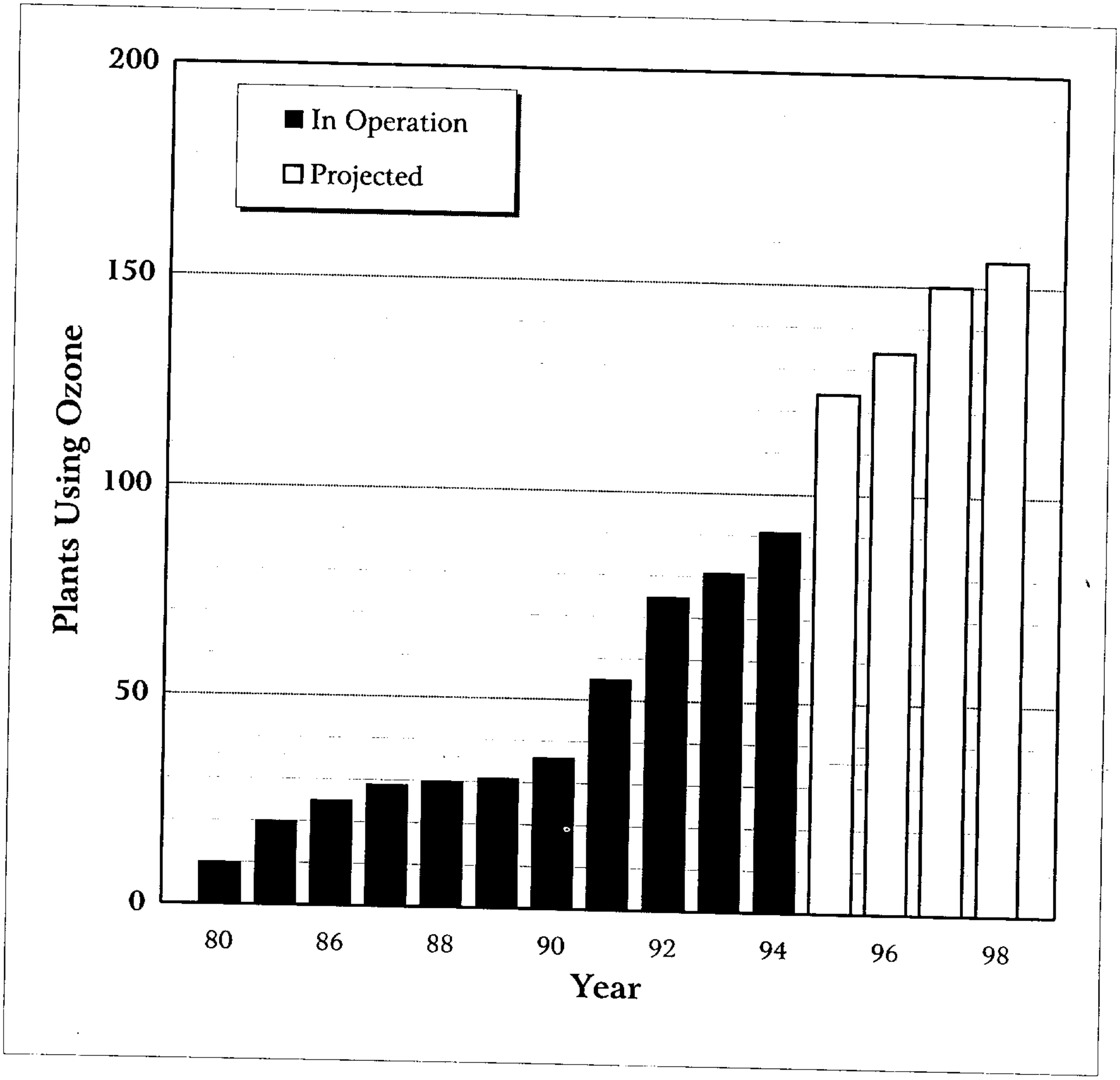


FIGURE 7-1

Ozonation Capacity in the United States
Source: Adapted from Rakness and Counters (1996)

Figure 7-2.* It may be noted that the ozone dose varies from 3.65 to 1.68 mg/L. The ozone demand also varies from 3.55 to 1.52 mg/L. The average annual ozone dose is approximately 2.5 mg/L.

Specific Energy

The energy used to produce ozone may vary depending on the operation of the ozone equipment.

The specific energy or unit energy required to generate ozone also depends upon the size of the ozonation facility. As the ozone generation capacity increases, the unit cost decreases. This relationship for an air-fed ozone generator facility is shown in Figure 7-3. The specific energy consumption for a given generation capacity can be obtained from Figure 7-3. The specific energy approaches 10.5 - 11 kWh/lb for a facility generating 400-500 lb/d ozone.

Unit Power Cost

The unit power cost ($/kWh) is dependent upon the approved rate of the electric utility. The unit cost of electricity may vary from $0.05/kWh to $0.10/kWh.

7.2 PROJECTION OF ENERGY DEMAND DUE TO INCREASED OZONATION PRACTICE IN THE UNITED STATES

The International Ozone Association provided us with a listing of potable water treatment plants that are using ozone in the United States, along with their capacities.* Specific engeries for different plant sizes are also shown in Figure 7-3. For ozone production that exceeds 300 lb/day, energy consumption is around 10 - 11 kWh/lb. Recently, more efficient small ozone generators been developed. The list included all plants in operation and those that were under construction up to May 1995. The information was used to develop the growth in ozonation capacity with

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*Personal communication

respect to time. This relationship is shown in Figure 7-4. Ozonation capacity is growing rapidly, increasing from 595 mgd in 1990 to 2951.3 mgd in 1995. It is projected that by the year 2000, the total ozonation capacity will reach 5.5 billion gallons per day, serving a population of approximately 33.2 million.

It is estimated that the average annual ozone dose in raw water is around 2.5 mg/L, or 20.85 lb per mgd. The ozone generation capacity in different years is plotted in Figure 7-5. It is estimated that the ozone generation capacity for water treatment will reach 115,100 lb/d by the year 2000. The average capacity of older water treatment plants is less than 10-mgd; new plants have a larger capacity. It is assumed that the average capacity of plants, including new and old, will be 20-mgd. The specific energy for a 20 mgd plant (see Figure 7-3) is 11 kWh/lb. The growth of energy requirements for ozonation facilities in the United States for different years is shown in Figure 7-5. The estimated energy demand for ozonation will reach 1.26 million kWh/d by the year 2000. At an average power cost of $0.08/kWh, the cost of energy (see Figure 7-6) for ozone generation will reach approximately $100,000 per day (Figure 7-7), or $40 million per year for the water utility industry.

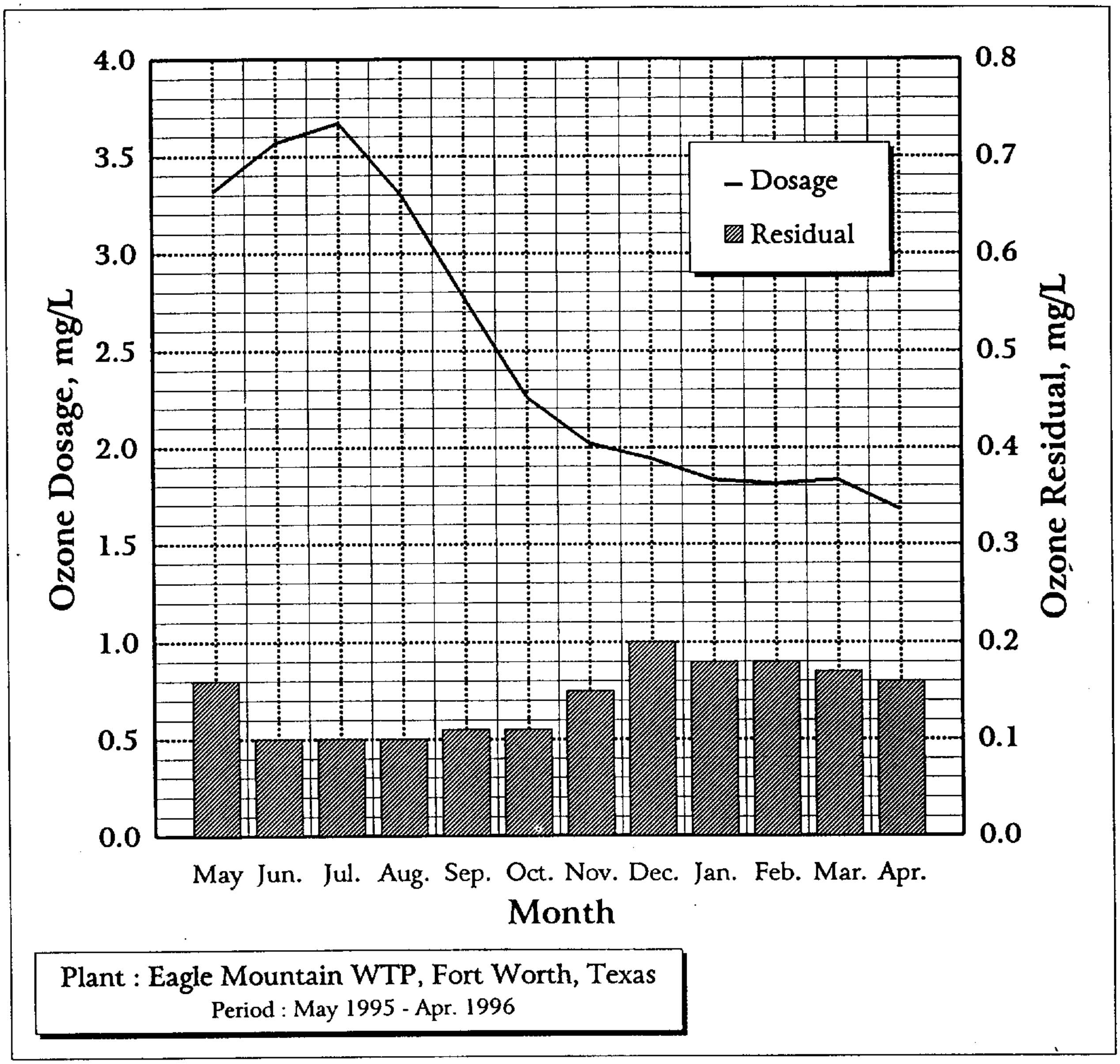

FIGURE 7-2
Monthly Average Ozone Dose and Residual
at Eagle Mountain Water Treatment Plant, Fort Worth, Texas

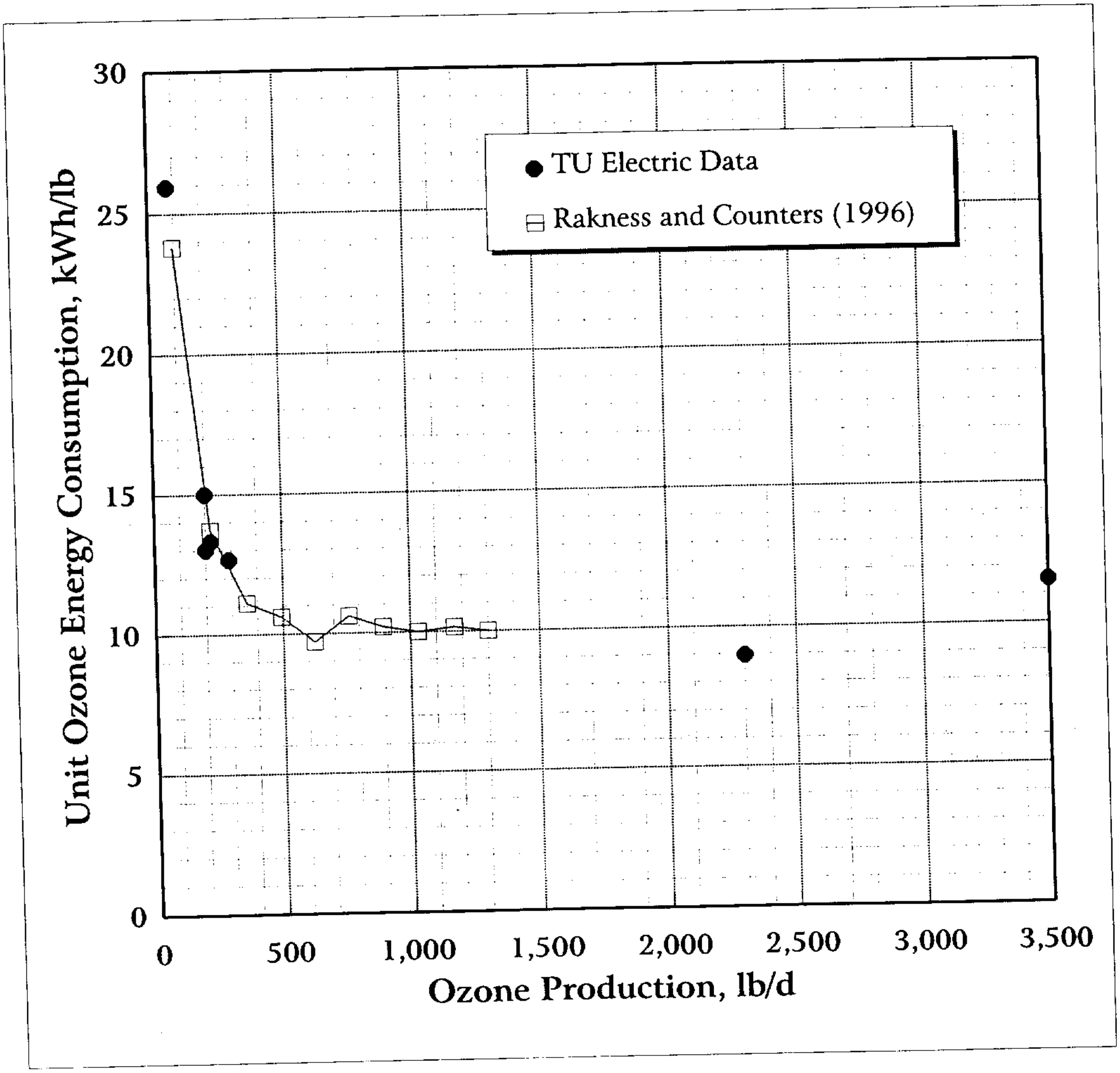

FIGURE 7-3

Specific Energy for Different Plant Sizes
Source: Adapted from Rakness and Counters (1996)

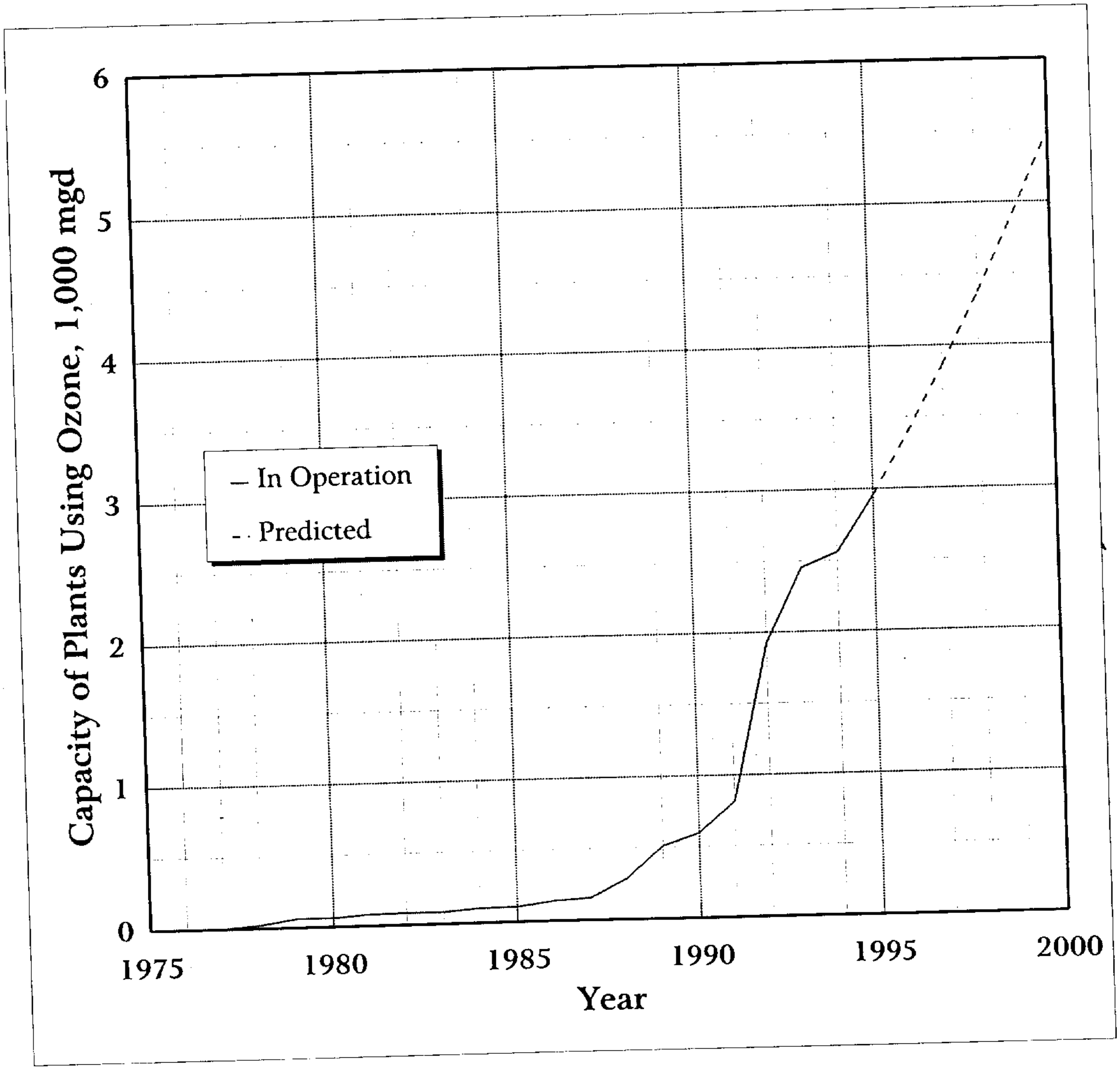

FIGURE 7-4

Capacity of Water Treatment Plants Using Ozone in the United States
Source: Personal communication with International Ozone Association

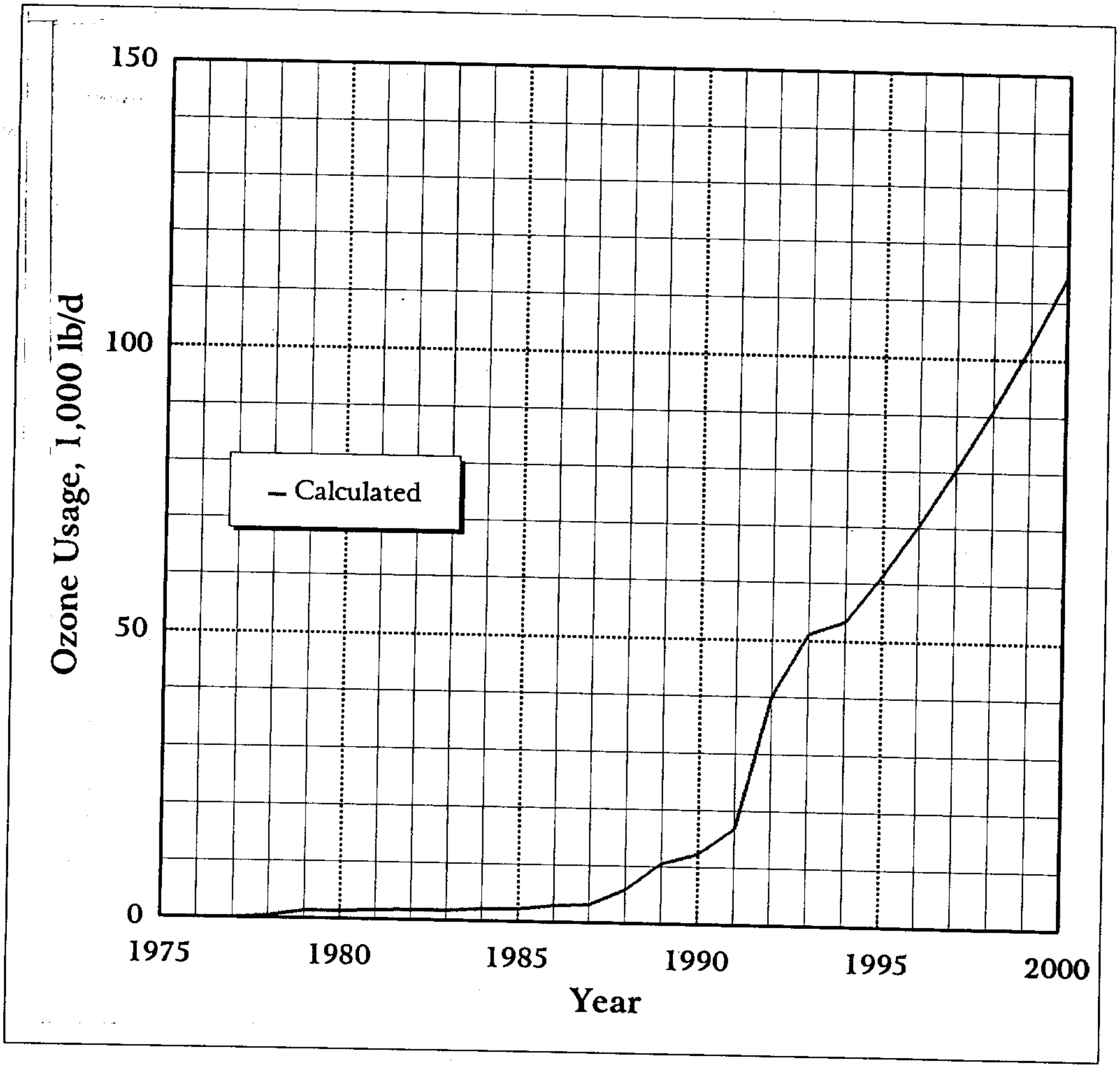

FIGURE 7-5
Estimation of Ozone Usage for Water Supply in the United States

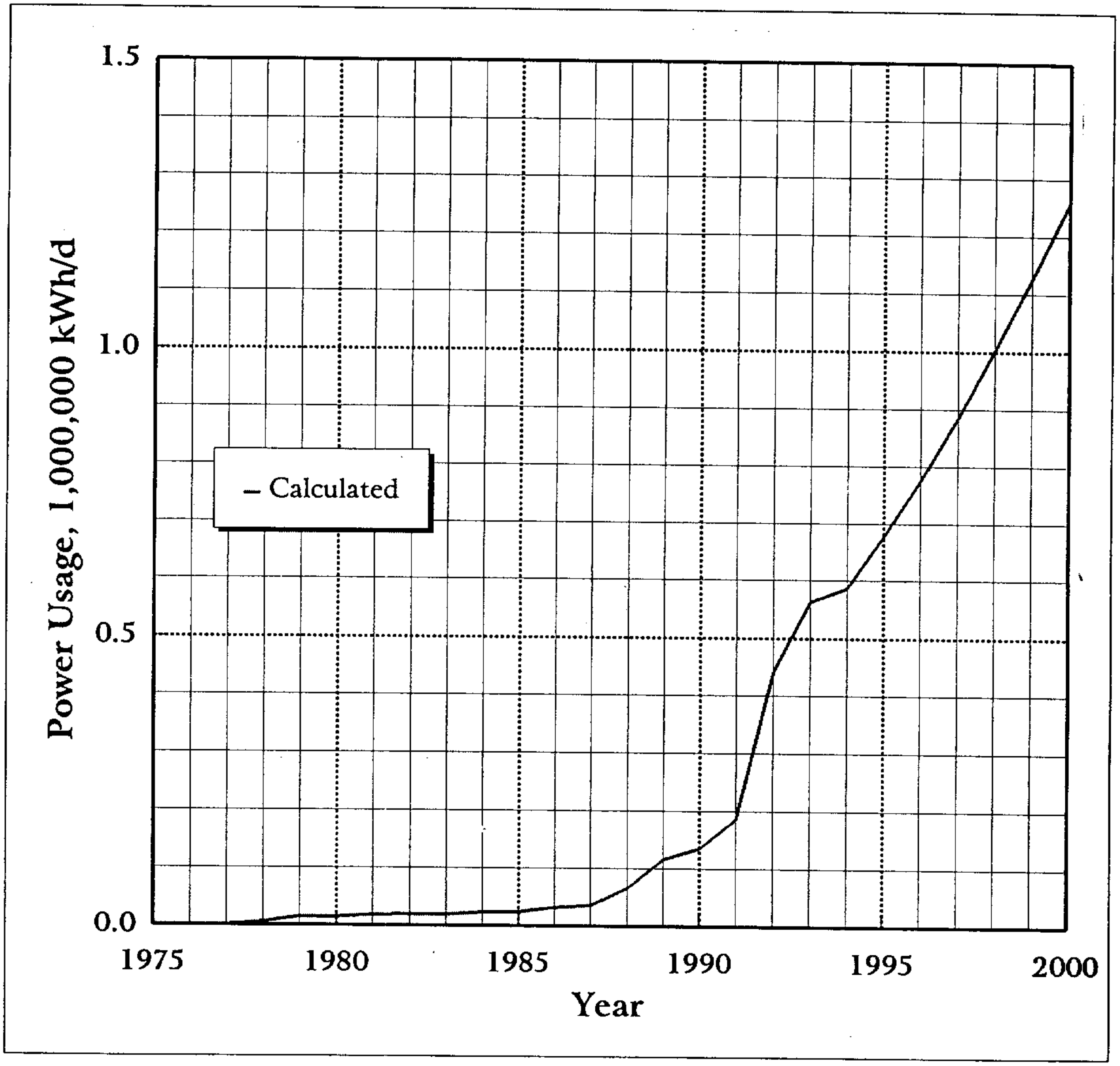

FIGURE 7-6
Estimation of Power Usage for Ozonation of Water Supply in the United States

CFW9513-1F\FIGURES.\KN

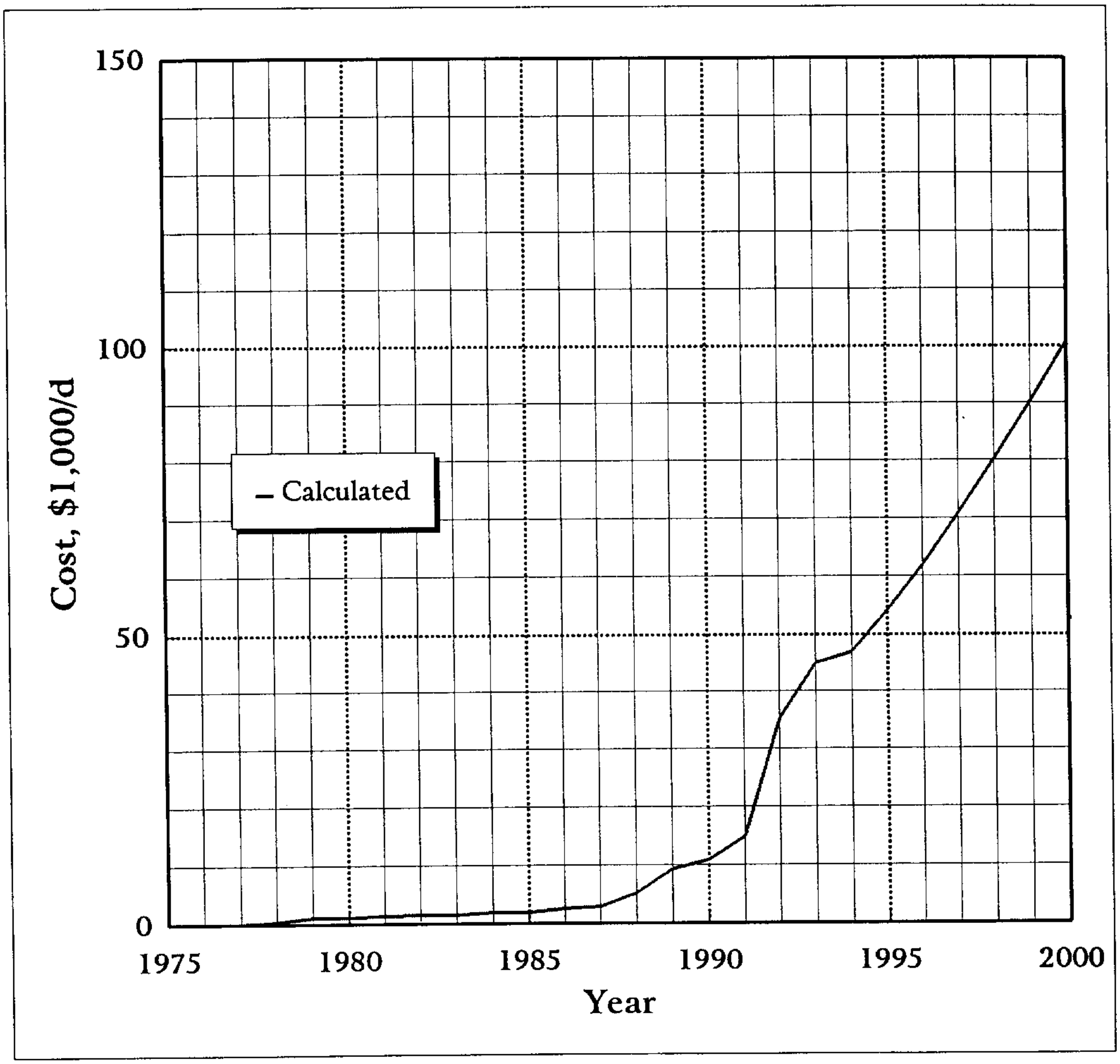

FIGURE 7-7

Estimation of Cost of Ozonation of Water Supply in the United States
(Based on $0.08/kWh)

CFW9513-1F\FIGURES.\KN

Chapter 8
DATA PROJECTION FOR FULL-SCALE PLANT OPERATION

The data developed from the lab-unit, bench-scale, and pilot plant studies are used in this chapter to assess the options of full-scale operation to remove arsenic and TOC. The minimum levels of arsenic and TOC concentrations achievable by modified coagulation and ozonation in full-scale treatment facilities are also presented. However, this information was collected through tests by using the water supply from the Fort Worth Rolling Hills Water Treatment Plant (RHWTP) in Fort Worth. Caution needs to be exercised when using this case study information for other applications.

8.1 APPLICATION POTENTIAL OF PHOTOCATALYTIC TREATMENT

Photocatalytic treatment using ultraviolet (UV) radiation with hydrogen peroxide (H_2O_2) and titanium oxide (TiO_2) beads in a controlled laboratory environment can effectively change As(III) to As(V). This innovative concept has been proven in the laboratory. However, the concept, at the present technological level, is not yet practical for the drinking water treatment industry. Engineering information such as the UV energy level, hydrogen peroxide concentration, amount of TiO_2, and mode of application and removal will need further development. The conversion rates from As(III) to As(V) and the removal mechanisms of arsenic in water will also need further research before this technology can be applied to the drinking water industry.

8.2 OPTIONS OF FULL-SCALE PLANT OPERATION TO REMOVE ARSENIC AND TOC

The RHWTP's water supply contains arsenic at a low level of 4 - 5 μg/L and TOC of 4 - 6 mg/L. The current arsenic level (MCL) in drinking water is 50 μg/L, which is expected to be lowered to 5 μg/L or less in the future. As mentioned in the jar test and pilot plant chapters of this report, in order to assess the arsenic removal by various treatment process combinations, arsenic As(V) and As(III) were added to raw water in both the laboratory jar tests and field pilot plant studies.

8.2.1 CONDITION I: EXISTING RAW WATER QUALITY, ARSENIC CONCENTRATION 4 - 6 μg/L

The conventional treatment process Fe(III) of about 3 mg/L, polymer, and pH adjustment is adequate to reduce 60 - 80% of the arsenic in drinking water. Therefore, under Condition I, water treatment plants should meet more stringent arsenic standards for drinking water.

8.2.2 CONDITION II: ASSUMED RAW WATER QUALITY, ARSENIC CONCENTRATION ELEVATED TO 30 μg/L

Option 1: Modify the treatment process to increase the Fe(III) dosage to 6 mg/L with polymer and pH adjustment to pH 8 to 8.5. The treated water will have 85 - 90% arsenic removal. The treated water will contain less than 5 μg/L of arsenic. TOC removal will be in the range of 20 - 30 %. Due to the increase in Fe(III) dosage, approximately 30% more sludge will be generated from the treatment.

Option 2: Keep the coagulant Fe(III) dosage or reduce slightly with the additional process of a preozonation dose of 1.5 mg/L. This process combination will enhance coagulation and result in slightly reduced sludge generation. Preozonation will also help the oxidation of As(III) to As(V) and will improve the removal of arsenic by coagulation and settling. However, preozonation does not remove TOC, but will alter the organic compounds and make them more readily removable by biological treatment.

8.2.3 CONDITION III: ASSUMED RAW WATER SUPPLY QUALITY, ARSENIC CONCENTRATION ELEVATED TO 50 μg/L

Option 1: Enhanced coagulation with a 9-mg/L dosage of Fe(III) can reduce As(V) to a 5 μg/L level in treated water. This is about two-and-one-half times the current coagulant dosages which produced 70% more sludge in treatment than the conventional treatment.

Option 2: Use a chemical coagulant Fe(III) dose of around 4.5-mg/L or less in conjunction with 2.5-mg/L preozonation. Such a combination, as demonstrated in jar tests, pilot plant, and other studies, will reduce the Fe(III) dose. Preozonation, therefore, will become an economically attractive option because of the small dosage of Fe(III) and the reduced sludge disposal costs. Additionally, finished water quality will improve significantly.

8.3 TREATMENT COST CHANGES TO REMOVE ARSENIC AND TOC

From the information developed through this study, the treatment cost changes for water treatment plants to implement arsenic removal are summarized in Table 8-1.

TABLE 8-1

TREATMENT COST CHANGES TO REMOVE ARSENIC

Arsenic Level (μg/L)			Process Modifications	Cost Changes		
Condition	Raw	Treated		Energy Demand	Additional Chemical Dosage	Additional Residue Management
I	5	<5	Present dosage of (Fe(III) = 3 mg/L)	No	No	No
II	30	<5	Option II - 1: Enhanced coagulation (Fe(III) = 6 mg/L)	No	Moderate increase	Moderate increase
			Option II - 2: coagulant (Fe(III) = 3 mg/L) + pre-ozonation (1.5 mg/L)	Significant increase	No	No
III	50 to 100	<5	Option III - 1: Enhanced coagulation (Fe(III) = 9 mg/L)	No	Significant increase	Significant increase
			Option III - 2: coagulation (Fe(III) = 4.5 mg/L) + pre-ozonation (2.5 mg/L)	Significant increase	Slight increase	Slight increase

8.4 PROJECTION OF TREATMENT COST INCREASES

The treatment costs for an increase of 10 mgd, 50 mgd, and 100 mgd to remove arsenic from the water supply are presented in Tables 8-2, 8-3, and 8-4. The capital and operation cost estimates are based on the following assumptions:

(A) Capital Investment Costs (1996 information)

(1) Coagulant Feed System Improvement Cost

10-mgd plant	$200,000
50-mgd plant	$800,000
100-mgd plant	$1,600,000

(2) Ozone System (including buildings, equipment, and reactors)

10-mgd plant	$1,700,000
50-mgd plant	$7,000,000
100-mgd plant	$12,000,000

(B) Operational Costs (1996 information)

(1) Coagulant: Liquid Ferric Sulfate = $0.040/lb

(2) Electricity: $0.08/kWh

(3) Ozone Dosage: 2.5 mg/L

(4) Sludge Disposal Cost = $160/ton

Figures 8-1 through 8-3 show the capital and operation cost increases to implement arsenic removal for water treatment plants of various sizes. At the present, the raw water supply of the Rolling Hills Water Treatment Plant has a very low arsenic level. No immediate action to remove arsenic is required at this plant.

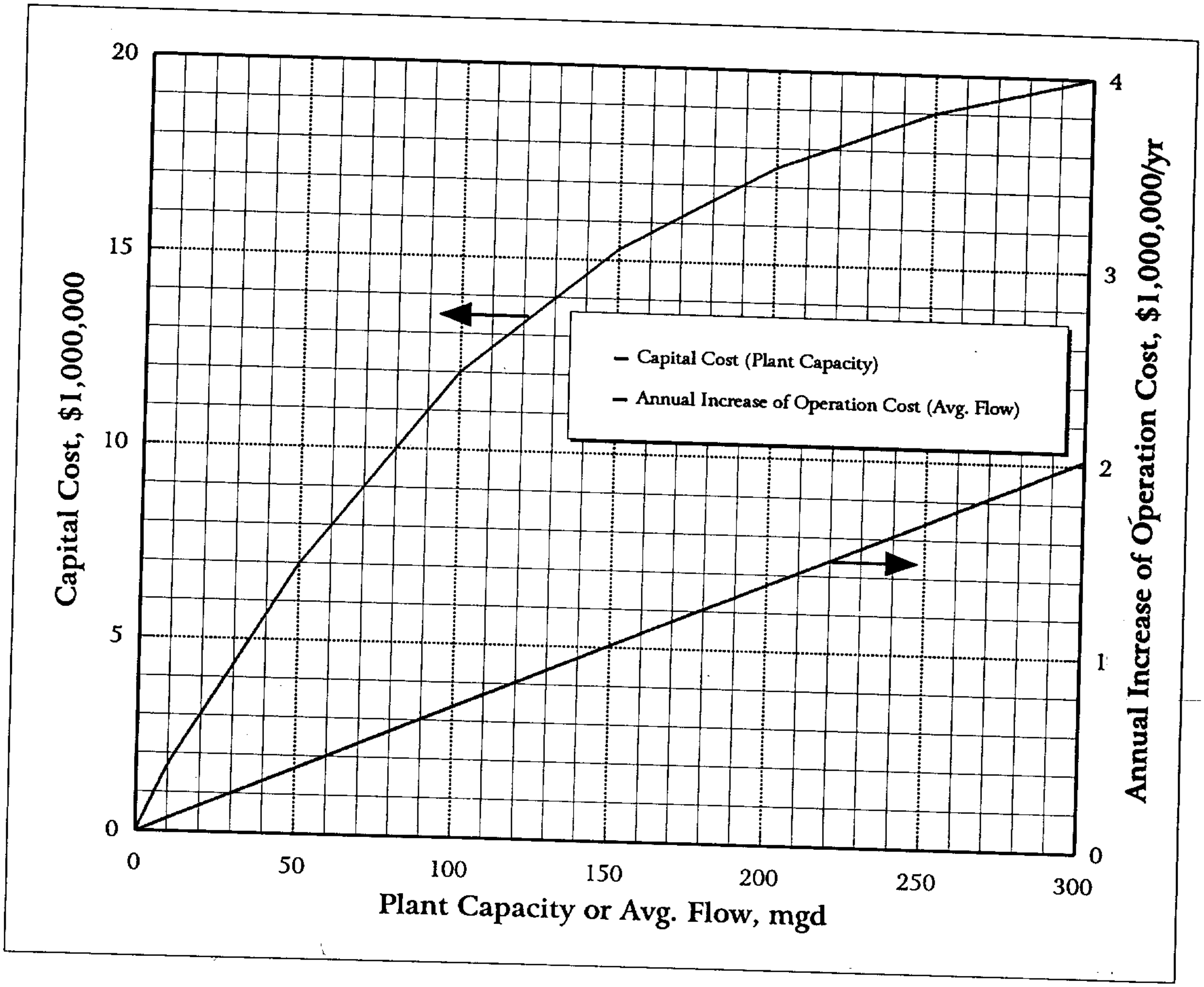

FIGURE 8-1
Ozone System and Operational Costs

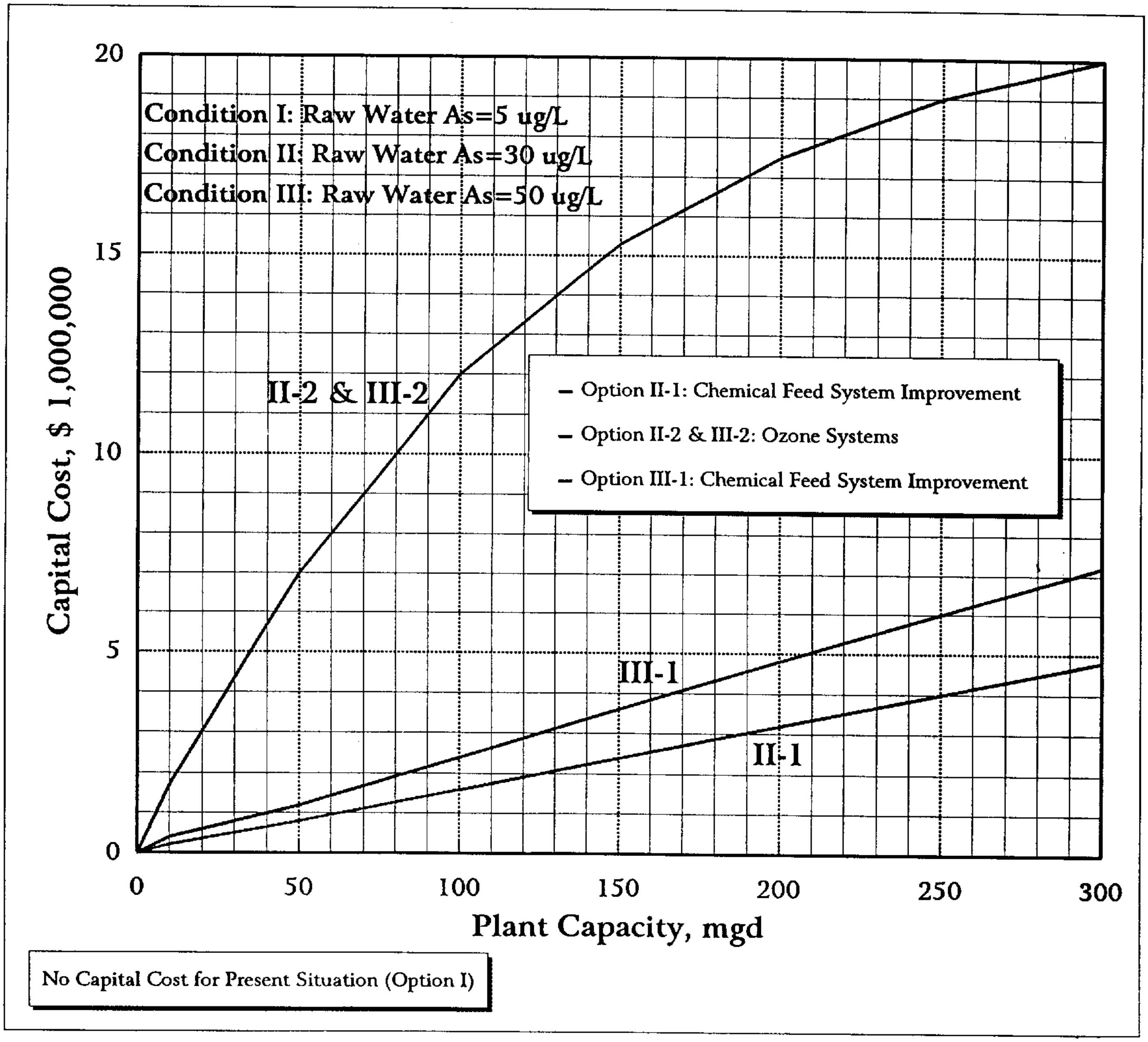

FIGURE 8-2

Capital Costs for Different Options for As Removal

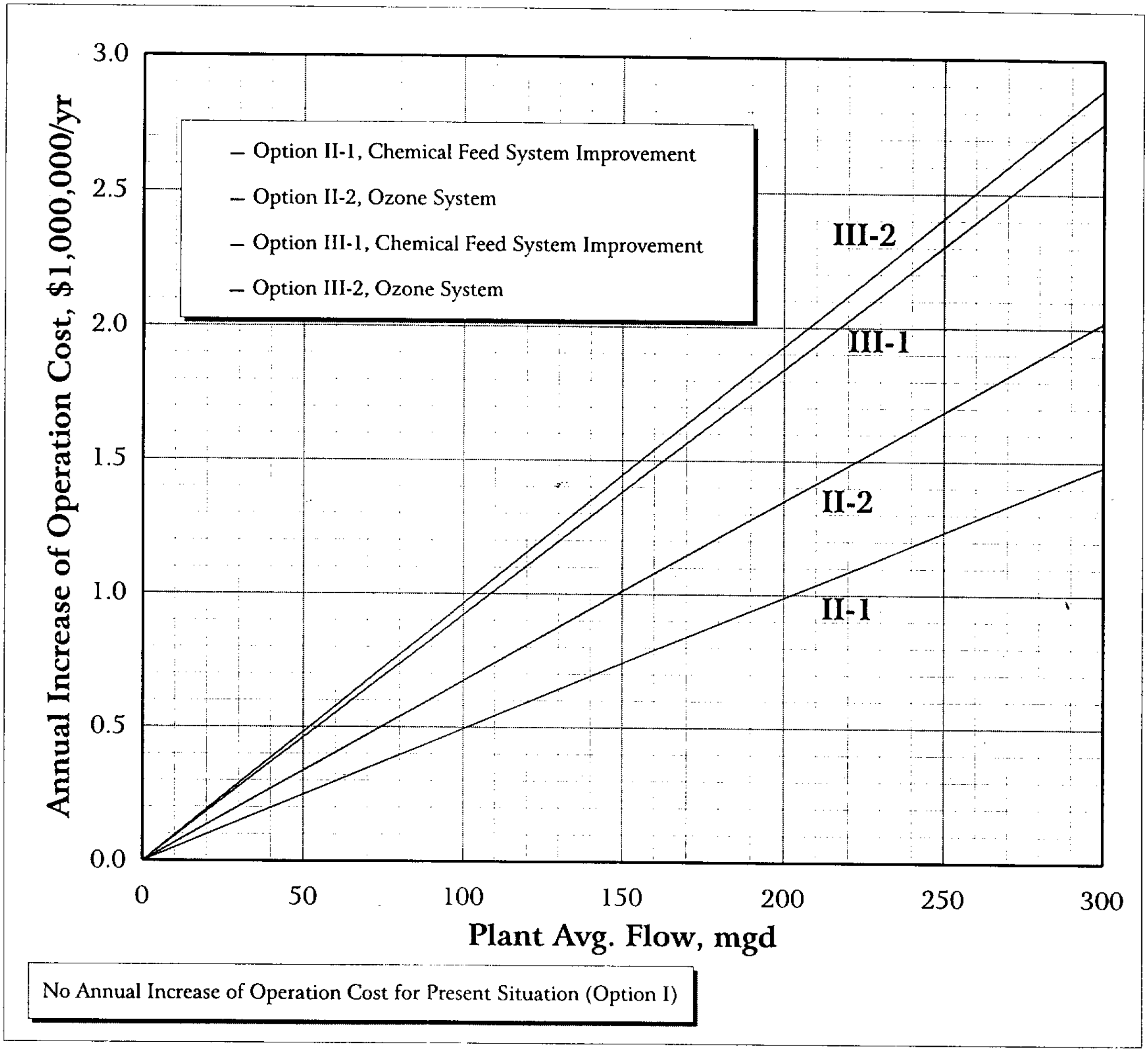

FIGURE 8-3

Operational Cost Increases Per Year
(Including Energy + Chemical + Sludge Management)

TABLE 8-2
TREATMENT COST INCREASES FOR 10-MGD

Arsenic Level (μg/L)			Treatment Option	Capital Cost ($)	Operation Cost ($/Yr.)			
Condition	Raw	Treated			Energy	Chemical	Sludge	Total
I	5	<5	No change					
II	30	<5	Option II - 1	$200,000		$34,800	$14,600	$49,400
			Option II - 2	$1,710,000	$67,500			$67,500
III	50 - 100	<5	Option III - 1	$400,000		$69,600	$26,800	$96,400
			Option III - 2	$1,710,000	$67,500	$17,400	$7,300	$92,200

TABLE 8-3
TREATMENT COST INCREASES FOR 50-MGD

Arsenic Level (μg/L)			Treatment Option	Capital Cost ($)	Operation Cost ($/Yr.)			
Condition	Raw	Treated			Energy	Chemical	Sludge	Total
I	5	<5	No change					
II	30	<5	Option II - 1	$800,000		$174,000	$73,100	$247,100
			Option II - 2	$7,000,000	$337,300			$337,300
III	50 - 100	<5	Option III - 1	$1,200,000		$347,800	$133,900	$481,700
			Option III - 2	$7,000,000	$337,300	$87,000	$36,500	$460,800

TABLE 8-4
TREATMENT COST INCREASES FOR 100-MGD

Arsenic Level (μg/L)			Treatment Option	Capital Cost ($)	Operation Cost ($/Yr.)			
Condition	Raw	Treated			Energy	Chemical	Sludge	Total
I	5	<5	No change					
II	30	<5	Option II - 1	$1,600,000		$348,000	$146,200	$494,200
			Option II - 2	$12,000,000	$674,500			$674,500
III	50 - 100	<5	Option III - 1	$2,400,000		$695,800	$267,900	$963,700
			Option III - 2	$12,000,000	$674,500	$174,000	$73,100	$921,600

8.5 OPTIONS AND COSTS OF SLUDGE DISPOSAL

The results of bench-scale experiments show that a high concentration of arsenic in coagulation sludge may be expected, even though a conventional coagulation process is utilized. To emphasize this point, a hypothetical case is presented and discussed as follows:

Suppose a conventional water treatment plant is treating water that has an initial TSS concentration of 10 mg/L in the raw water source, and a Fe(III) dosage of 2.5 mg/L is utilized. The arsenic concentrations in dry and wet sludge will depend upon the initial arsenic concentration in the raw water. The calculated arsenic concentrations in dry and wet sludge for raw water arsenic concentrations for 5 to 50 μg/L are presented in Table 8-5. The arsenic concentrations in liquid sludge are calculated by assuming that the sludge volume is 5 percent of the plant capacity. It may be noted that the arsenic concentration in dry sludge at raw water arsenic concentration of 5 μg/L is around 290 mg/kg. This value exceeds the permissible limit of 75 mg/kg for arsenic in sludge for land application. Therefore, land application of this sludge will not be allowed. Whereas co-disposal of municipal solid wastes (MSW) and land filling in a secure landfill may be the possible options. On the other hand, discharge of liquid sludge into a POTW may be acceptable as the concentration of arsenic may be below the local discharge limits. For instance, a limit of 0.4 mg/L arsenic is applied in the industrial discharge at a local wastewater treatment plant. This limit would allow liquid sludge disposal in the POTW from a water treatment plant that has arsenic concentrations up to 20 μg/L in the raw water.

The cost for disposal of water treatment plant sludge with elevated arsenic is very difficult to project because no historical plant record for sludge disposal data is available. The current practice of liquid sludge disposal in a POTW is an acceptable practice as long as the raw water concentration of arsenic is below 20 μg/L. The cost of co-disposal of sludge with municipal solid waste is less than \$20/ton. The estimated cost of water treatment sludge in secure landfills is around \$40/ton.

TABLE 8-5
ARSENIC CONCENTRATION IN SLUDGE AND DISPOSAL OPTIONS

Raw Water As Concentration (μg/L)	As Concentration in Sludge		Disposal Options			
	Dry Sludge[a] (mg /kg)	Liquid Sludge[b] (mg/L)	Land Application	Liquid Sludge Discharge into Sewer[c]	Co-disposal with MSW	Disposal in Secure Landfill
As ≤ 5	≤ 290	0.083	No	Yes	Yes	Yes
5 < As ≤ 10	≤ 630	0.178	No	Yes	Yes	Yes
10 < As ≤ 20	≤ 1300	0.369	No	Yes	Yes	Yes
20 < As ≤ 30	≤ 1970	0.559	No	No	Yes	Yes
30 < As ≤ 50	≤ 3310	0,941	No	No	Yes	Yes

[a] Fe(III) dosage of 2.5 mg/L and TSS concentration of 10 mg/L in raw water
[b] Sludge volume is 5 % of plant influent flow
[c] Arsenic limit for discharge of liquid sludge in a POTW is 0.4 mg/L

Chapter 9
CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the arsenic concentration profile in Texas surface water sources and enhanced coagulation studies, it can be concluded that the arsenic level in Texas waters is quite low, and water utilities can easily achieve the anticipated arsenic standard by enhanced coagulation in a conventional water treatment plant. It may be further concluded that preozonation can oxidize arsenite to easily removable arsenate species. Additionally, arsenite species can also be oxidized to arsenate or reduced to elemental arsenic by use of electrotechnologies. Conclusions more specific to different components of the research program are presented below.

9.1 OCCURRENCE OF ARSENIC IN SURFACE WATER SOURCES IN TEXAS

The arsenic concentration profile map of surface water sources in Texas developed from TNRCC data files, clearly shows that major areas in the State have arsenic concentrations of less than 5 μg/L. Only a few hot spots in Texas have arsenic concentrations in the range of 21 - 30, 31 - 40, and over 40 μg/L.

9.2 BENCH-SCALE STUDY OF ENHANCED COAGULATION

In this study, the standard jar test experiments were conducted with arsenic-spiked water samples to assess the removal of arsenic and NOM by the enhanced coagulation process. Research findings are presented in the following areas: (1) coagulation diagrams, (2) preozonation, (3) sludge production and characterization, and (4) arsenic removal mechanisms. The major conclusions are summarized below.

COAGULATION DIAGRAMS

The coagulation diagrams prepared for the targeted constituents — turbidity, arsenic, organic carbon, and UV 254 absorbance — clearly show the following:

- A strong dependence of coagulation behaviors on pH and coagulant dosage was observed.

- Optimum turbidity and total arsenic removal in settled water with ferric sulfate were observed at pH 4.5 and 8.5 - 9, with an Fe(III) dosage of 8 mg/L. The poorest removal of these targeted constituents was in the pH range of 6 - 7. There was a linear relationship between turbidity and total arsenic removal, indicating that most of the arsenic is readily converted from soluble into particulate form. Therefore, dissolved arsenic concentrations of 2 μg/L or less can be achieved if turbidity is effectively removed from coagulated water by sedimentation and filtration processes.

- Optimal removal of TOC and reduction of UV 254 absorbance with ferric sulfate coagulation was at pH below 6.5 with a Fe(III) dosage of 8 mg/L. The poorest removal of TOC and reduction in UV 254 absorbance occurred in the pH range of 7.5 - 9.

- Ferric chloride produced coagulation diagrams of targeted constituents that had similar trends as those with ferric sulfate. There were, however, less pH dependence and higher removal efficiencies. Optimum turbidity and arsenic removals occurred at pH 8 - 8.5 and at an Fe(III) dosage of 6 mg/L, whereas the poorest pH conditions were in the range of 6 - 6.5. Optimum TOC removal occurred below pH 6.5 and at an Fe(III) dosage of 14 mg/L, and the poorest removal was observed above pH 7.5. Optimum conditions for reduction in UV 254 absorbance were at pH below 6 and in the range of 9 - 9.5, with an Fe(III) dosage of 6 mg/L, whereas the worst reduction in UV254 absorbance occurred at pH 7 - 8.5.

- The removal of targeted constituents with alum reveals a trend similar to that with Fe(III)-based coagulants. Alum coagulation showed improved turbidity and total arsenic removals at natural pH, whereas an improved reduction in UV 254 absorbance was observed under acidic conditions (around pH 5.5).

PREOZONATION

The experimental results of coagulation with and without preozonation showed the following :

- Without preozonation, As(III) is partially removed (65 - 80 percent) by enhanced coagulation at an Fe(III) dosage greater than 8.4 mg/L. In comparison, As(V) is 90 - 95 percent removed under similar conditions.
- Preozonation enhanced the removal of As(III). The removal approached that of As(V) without preozonation.
- Preozonation also improved turbidity removal, which may have also influenced the removal of total arsenic.
- Preozonation followed by ferric chloride coagulation is a more effective combination for As(III) and turbidity removals than ferric sulfate after preozonation.

SLUDGE PRODUCTION

The major findings of sludge production experiments are as follows:

- The amount of sludge mass produced is proportional to the amount of Fe(III) applied in the coagulation process. As a result, a larger quantity of sludge will be produced by enhanced coagulation than by conventional coagulation.
- The sludge volume shows a nonlinear relationship with respect to the amount of Fe(III) applied.
- Soluble arsenic can be immobilized at a relatively low coagulant dosage by adsorption onto the floc, as long as the quantity of sludge still remains small. As a result, the arsenic concentration in sludge, if a conventional coagulation process is used, will be significantly higher than that from an enhanced coagulation process.

ARSENIC REMOVAL MECHANISM

The major findings of the arsenic removal mechanism experiment are as follows:

- Arsenic removal involves two major steps: (1) an immobilization step in which soluble arsenic is converted into particulate arsenic by adsorption and/or coprecipitation mechanisms and (2) a separation step whereby the newly formed particulate arsenic is removed from the aqueous system by coagulation, flocculation, sedimentation, and filtration mechanisms.
- Both steps influence overall arsenic removal. This influence can be determined by analysis of dissolved and total arsenic removal.
- Langmuir adsorption isotherms apply to both dissolved and total arsenic removal and can serve as a useful tool in predicting arsenic removal by coagulation.
- Because of the high immobilization capacity of arsenic, conventional coagulation can achieve the desired level of arsenic in finished water as long as the initial arsenic concentration in raw water is at a low to medium level. Enhanced coagulation may be necessary only when (1) there is a high initial arsenic concentration in raw water, (2) immobilization is greatly interfered with by other contaminants, (3) separation of arsenic-carrying particles needs to be enhanced, and/ or (4) ultimate options for sludge disposal or reuse require lower levels of arsenic concentration in sludge.

9.3 BENCH-SCALE STUDY OF ADVANCED PHOTOCATALYTIC TECHNOLOGIES

Two new technologies for improving the removal of As(III) were demonstrated by proof-of-concept experiments: (a) photocatalytic oxidation of As(III) to As(V) and (b) photocatalytic reduction of As(III) to As(0).

PHOTOCATALYTIC OXIDATION OF ARSENITE

In this study, these were the major findings:

- Ultraviolet (UV) radiation in conjunction with hydrogen peroxide (H_2O_2) and titanium oxide (TiO_2) is very effective for oxidation of As(III) to As(V).

- Hydrogen peroxide also oxidized As(III) in the dark, but the oxidation state was much slower than when radiation was used.

PHOTOCATALYTIC REDUCTION OF ARSENITE

In this method, the preliminary results are very encouraging. Due to the possible photocatalytic reduction of As(III) to As(0) onto the TiO_2 surface, the concentration of dissolved arsenic in the water sample was monitored as a function of TiO_2 irradiation time by a UV-visible spectrophotometric method. However, the feasibility still remains inconclusive. Further efforts are in progress.

9.4 PILOT PLANT STUDIES

- Arsenate (As^{+5}) removal percentages of 85% to 95% are relatively simple to achieve when treating water with a combination of iron-salt coagulants, adequate settling and filtration.

- Arsenite (As^{+3}) removal percentages of 85% to 95% are possible when preozonation is used to treat water. The ozone converts arsenite to the more easily removed arsenate.

- During the pilot plant operation, when the water pH is above 9, the removal of arsenic occurs mainly through settling. However, when the water pH is below 9, the removal of arsenic is accomplished by the combined treatment of settling and filtration.

- The use of polymer or ozone results in similar removals of TOC, turbidity, and arsenate. However, using ozone to enhance coagulation will generate less sludge than the use of additional polymer, and coagulant should be realized.

9.5 ENERGY CONSUMPTION DUE TO OZONATION

The purpose of evaluating the energy consumption due to ozonation is to address the vital issue of energy demand nationwide as more water treatment plants utilize the ozonation process as an oxidizing agent and disinfectant. To have an estimated 2.5 mg/L ozone dosage for a total planned 5.5 billion gallons of water treated per day by ozonation in the year 2000, the annual electricity cost for ozonation at all water treatment plants in the United States will reach $40,000,000 per year.

The ozone dosage at Fort Worth's Eagle Mountain Water Treatment Plant varies from 1.68 to 3.65 mg/L. The energy reused for ozone generation is approximately 11 kWh/lb.

9.6 DATA PROJECTIONS FOR FULL-SCALE PLANT

One important goal of this arsenic removal study is to use the lab scale and pilot plant data to assess the treatment options for a full-scale plant operation.

According to the pilot plant and jar test data, the raw water supply of the Rolling Hills Water Treatment Plant does not have arsenic problems. Due to the low arsenic level in the water, there will not be a problem meeting the current 50 μg/L standards and the possible proposed 5 - 10 μg/L standards.

If an elevated arsenic level (30 - 50 μg/L) shows up in the raw water supply in the future, enhanced coagulation can remove arsenic successfully.

Ozone is also effective in enhancing arsenic removal by improving coagulation and settling. By not increasing the chemical dosage, sludge production can be maintained at the same level. Other benefits of using ozonation are well documented in the literature and in plant operations. Discussions are limited in this report.

Increase in capital and operational costs resulting from different levels of arsenic removal are covered in this report. This information can be used for future planning purposes.

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APPENDICES

APPENDIX A

SUMMARY OF EXPERIMENTAL CONDITIONS

TABLES

TABLE A-1
Summary of Operational Conditions for Coagulation Diagram Experiments

No.	TEST CODE	SPIKED WATER BATCH CODE	CHEMICAL CONDITIONING										MAJOR OBJECTIVE OF RUN
			Spiking		Coagulant			Chemicals Utilized for pH Adjustment			Other Chemicals		
			As (III)	As (V)	Ferric Sulfate	Ferric Chloride	Alum	Sulfuric Acid	Sodium Hydroxide	Quick Lime	Ozone	Kaolin	
1	JE-7	SWS-1		×	×								Final pH=6.7-7.4 (Natural)
2	JE-8				×								Final pH=6.7-7.6 (Natural)
3	JE-9				×			×					Final pH=6.6-6.7
4	JE-10				×			×					Final pH=6.0-6.1
5	JE-11				×			×					Final pH=5.1-5.3
6	JE-12				×				×				Final pH=7.3-8.8
7	JE-16				×					×			Final pH=8.5-8.8
8	JE-17				×					×			Final pH=9.1-9.3
9	JE-18				×			×					Final pH=5.2-6.1
10	JE-19	SWS-2		×		×							Final pH=6.0-7.1
11	JE-20				×								Final pH=6.3-7.1
12	JE-21					×		×					Final pH=6.5-6.6
13	JE-22					×		×					Final pH=6.1-6.2
14	JE-23					×		×					Final pH=5.4-5.6
15	JE-24				×			×					Final pH=4.3-4.8
16	JE-25					×				×			Final pH=7.4-8.4
17	JE-26				×					×			Final pH=8.6
18	JE-27					×				×			Final pH=9.0-9.3
19	JE-28					×				×			Final pH=10.6-10.7
20	JE-29						×						Final pH=6.1-7.3
21	JE-30						×	×					Final pH=5.4-5.6

TABLE A-2
Summary of Operational Conditions for Preozonation Experiments

No.	TEST CODE	SPIKED WATER BATCH CODE	CHEMICAL CONDITIONING										MAJOR OBJECTIVE OF RUN
			Spiking		Coagulant			Chemicals Utilized for pH Adjustment			Other Chemicals		
			As (III)	As (V)	Ferric Sulfate	Ferric Chloride	Alum	Sulfuric Acid	Sodium Hydroxide	Quick Lime	Ozone	Kaolin	
1	JE-37	SWS-4	×			×							As(III) without Preozonation
2	JE-51	SWS-6-1		×		×					×		As(V) with Preozonation
3	JE-52	SWS-6-2	×			×					×		As(III) with Preozonation
4	JE-53					×					×		As(III) with Preozonation
5	JE-54				×						×		As(III) with Preozonation
6	JE-55	SWS-6-3	×			×							As(III) without Preozonation
7	JE-56				×								As(III) without Preozonation

TABLE A-3
Summary of Operational Conditions for Sludge Production Experiments

No.	TEST CODE	SPIKED WATER BATCH CODE	CHEMICAL CONDITIONING										MAJOR OBJECTIVE OF RUN
			Spiking		Coagulant			Chemicals Utilized for pH Adjustment			Other Chemicals		
			As (III)	As (V)	Ferric Sulfate	Ferric Chloride	Alum	Sulfuric Acid	Sodium Hydroxide	Quick Lime	Ozone	Kaolin	
1	JE-31	SWS-3				×		×					Fe(III) Dosages of 11.2 & 16.8 mg/L
2	JE-32					×		×					Fe(III) Dosages of 11.2 & 16.8 mg/L
3	JE-33					×		×					Fe(III) Dosage of 5.6 mg/L
4	JE-34					×		×					Fe(III) Dosage of 2.8 mg/L
5	JE-35				×			×					Fe(III) Dosages of 8.4 & 12.6 mg/L
6	JE-36				×			×					Fe(III) Dosages of 2.1 & 4.2 mg/L

TABLE A-4
Summary of Operational Conditions for Arsenic Removal Mechanism Experiments

No.	TEST CODE	SPIKED WATER BATCH CODE	CHEMICAL CONDITIONING										MAJOR OBJECTIVE OF RUN
			Spiking		Coagulant			Chemicals Utilized for pH Adjustment			Other Chemicals		
			As (III)	As (V)	Ferric Sulfate	Ferric Chloride	Alum	Sulfuric Acid	Sodium Hydroxide	Quick Lime	Ozone	Kaolin	
1	JE-39	SWS-5-1		×		×							$[\text{As}]_o$= 94.8 μg/L, $[\text{Turb}]_o$=0.23NTU, & Final pH=6.6-7.5 (Natural)
2	JE-40					×						×	$[\text{As}]_o$= 94.8 μg/L, $[\text{Turb}]_o$=42.4NTU, & Final pH=6.7-7.3 (Natural)
3	JE-41					×						×	$[\text{As}]_o$= 94.8 μg/L, $[\text{Turb}]_o$=10.7NTU, & Final pH=6.6-7.4 (Natural)
4	JE-42					×						×	$[\text{As}]_o$= 94.8 μg/L, $[\text{Turb}]_o$=21.3NTU, & Final pH=6.5-7.4 (Natural)
5	JE-43					×		×				×	$[\text{As}]_o$= 94.8 μg/L, $[\text{Turb}]_o$=21.5NTU, &Final pH=6.1-6.3
6	JE-44	SWS-5-2		×		×							$[\text{As}]_o$= 47.4 μg/L, $[\text{Turb}]_o$=0.23NTU, & Final pH=6.6-7.3 (Natural)
7	JE-45					×		×					$[\text{As}]_o$= 47.4 μg/L, $[\text{Turb}]_o$=0.23NTU, & Final pH=6.1-6.3
8	JE-46					×						×	$[\text{As}]_o$= 47.4 μg/L, $[\text{Turb}]_o$=44.6NTU, & Final pH=6.6-7.2 (Natural)
9	JE-47					×		×				×	$[\text{As}]_o$= 47.4 μg/L, $[\text{Turb}]_o$=44.6NTU, & Final pH=6.1-6.2
10	JE-49	SWS-5-3		×		×							$[\text{As}]_o$= 23.7 μg/L, $[\text{Turb}]_o$=0.23NTU, & Final pH=6.6-7.5 (Natural)
11	JE-50	SWS-5-4		×		×							$[\text{As}]_o$=11.9 μg/L, $[\text{Turb}]_o$=0.25NTU, & Final pH=6.6-7.4 (Natural)

APPENDIX B

EXPERIMENTAL DADA SHEETS

B1 EXPERIMENTAL DATA SHEETS FOR COAGULATION DIAGRAM EXPERIMENTS

B2 EXPERIMENTAL DATA SHEETS FOR PREOZONATION EXPERIMENTS

B3 EXPERIMENTAL DATA SHEETS FOR SLUDGE PRODUCTION EXPERIMENTS

B4 EXPERIMENTAL DATA SHEETS FOR ARSENIC REMOVAL MECHANISM EXPERIMENTS

APPENDIX B1

EXPERIMENTAL DATA SHEETS

FORCOAGULATION DIAGRAM EXPERIMENTS

TABLES

Experiments with Water Sample SWS-1:

Experiments with Water Sample SWS-2:

TABLE B1-1

Water Sample Quality Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Spiked Water Sample Batch Code : *SWS-1* Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity mg/L as CaCO3	Total Hardness mg/L as CaCO3	Turbidity Original NTU	Turbidity Filtered NTU	Particle Count 2 um Cuml. No./mL	Particle Count 5 um	Particle Count 10 um	Particle Count 20 um	Arsenic Spiked with III	Arsenic Spiked with V	Arsenic Total mg/L	Arsenic Dissolved mg/L	Organic Carbon Total mg/L	Organic Carbon Dissolved mg/L	UV 254 1/cm	Total THMFP mg/L	Remark
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*05-22-95*	*20.5*	*7.95*			*16.0*							*X*	*10.8*						Arsenic Analysis Data from : NDRC No. D95-4668
2	*05-25-95*	*18.5*	*7.90*	*88*		*16.0*							*X*	*10.4*	*10.7*	*4.0*	*5.1*	*0.147*	*1.40*	Arsenic & Org. C. Analysis Data from : NDRC No. D95-4821 UV & THMFP Analysis Data from : FWWDLS No. AA05816 FWWDLS No. AA05828
3	*05-26-95*	*18.5*	*8.17*	*90*		*16.1*	*0.79*						*X*	*11.7*	*9.9*	*4.4*	*4.3*	*0.145*	*1.00*	Arsenic & Org. C. Analysis Data from : NDRC No. D95-4696 UV & THMFP Analysis Data from : FWWDLS No. AA05848 FWWDLS No. AA05852
4	*05-31-95*	*20.5*	*7.98*	*84*		*15.8*	*0.78*						*X*							
5	*06-01-95*	*20.5*	*8.03*	*87*		*15.6*	*0.76*						*X*	*11.0*						Arsenic Analysis Data from : NDRC No. D95-5064
6	*06-06-95*	*23.8*	*8.07*	*88*		*14.6*	*0.74*						*X*							
7	*06-12-95*	*21.0*	*8.17*	*90*	*105*	*15.3*	*0.78*						*X*	*12.8*	*12.0*	*3.2*	*3.2*	*0.141*	*1.00*	Arsenic & Org. C. Analysis Data from : NDRC No. D95-5393 UV & THMFP Analysis Data from : FWWDLS No. AA05998 FWWDLS No. AA06005
8	*06-29-95*	*22.6*	*8.04*	*86*		*16.80*	*0.79*						*X*							
Number of Samples	-	*8*	*8*	*7*	*1*	*8*	*6*	-	-	-	-	-	-	*5*	*3*	*3*	*3*	*3*	*3*	
Average Ambient Value	-	*20.7*	*8.0*	*88*	*105*	*15.8*	*0.77*	-	-	-	-	-	-	*11.3*	*10.9*	*3.9*	*4.2*	*0.144*	*1.13*	

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B1-2

Wet Chemistry Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code :** *CFW9513* **Page :** *1/3*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-7	*05-25-95*	*1*	*SWS-1*	*20*	*2.1*										
		2		*40*	*4.2*										
		3		*60*	*6.3*										
		4		*80*	*8.4*										
		5		*100*	*10.5*										
		6		*120*	*12.6*										
JE-8	*05-26-95*	*1*	*SWS-1*	*20*	*2.1*										
		2		*40*	*4.2*										
		3		*60*	*6.3*										
		4		*80*	*8.4*										
		5		*100*	*10.5*										
		6		*120*	*12.6*										
JE-9	*05-31-95*	*1*	*SWS-1*	*20*	*2.1*					*0.625*					
		2		*40*	*4.2*					*0.500*					
		3		*60*	*6.3*					*0.375*					
		4		*80*	*8.4*					*0.250*					
		5		*100*	*10.5*					*0.125*					
		6		*120*	*12.6*										

TABLE B1-2 (continued)

Wet Chemistry Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *2/3*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-10	*06-01-95*	*1*	*SWS-1*	*20*	*2.1*					*1.200*					
		2		*40*	*4.2*					*1.100*					
		3		*60*	*6.3*					*1.000*					
		4		*80*	*8.4*					*0.900*					
		5		*100*	*10.5*					*0.775*					
		6		*120*	*12.6*					*0.650*					
JE-11	*06-01-95*	*1*	*SWS-1*	*20*	*2.1*					*1.550*					
		2		*40*	*4.2*					*1.450*					
		3		*60*	*6.3*					*1.350*					
		4		*80*	*8.4*					*1.250*					
		5		*100*	*10.5*					*1.125*					
		6		*120*	*12.6*					*1.000*					
JE-12	*06-06-95*	*1*	*SWS-1*	*20*	*2.1*						*0.200*				
		2		*40*	*4.2*						*0.250*				
		3		*60*	*6.3*						*0.300*				
		4		*80*	*8.4*						*0.350*				
		5		*100*	*10.5*						*0.400*				
		6		*120*	*12.6*						*0.450*				

TABLE B1-2 (continued)
Wet Chemistry Data
- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code :** *CFW9513* **Page :** *3/3*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-16	*06-12-95*	*1*	*SWS-1*	*20*	*2.1*							*7.8*			
		2		*40*	*4.2*							*12*			
		3		*60*	*6.3*							*15*			
		4		*80*	*8.4*							*18.6*			
		5		*100*	*10.5*							*22.2*			
		6		*120*	*12.6*							*27*			
JE-17	*06-12-95*	*1*	*SWS-1*	*20*	*2.1*							*38.4*			
		2		*40*	*4.2*							*42*			
		3		*60*	*6.3*							*45.6*			
		4		*80*	*8.4*							*49.2*			
		5		*100*	*10.5*							*53.4*			
		6		*120*	*12.6*							*58.2*			
JE-18	*06-29-95*	*1*	*SWS-1*	*80*	*8.4*					*0.900*					
		2		*100*	*10.5*					*0.775*					
		3		*40*	*4.2*					*1.450*					
		4		*60*	*6.3*					*1.350*					
		5		*80*	*8.4*					*1.250*					
		6		*100*	*10.5*					*1.125*					

TABLE B1-3
Treatability Data
- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process*　　Job Code : *CFW9513*　　Page : *1/3*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Spiked with		Arsenic		Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 um	5 um	10 um	20 um	III	V	Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL						mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-7	1	SWS-1	7.43	82		13.3							X	12.4	2.0	4.2	7.9	0.144	4.2	Arsenic & Org. C. Analysis Data from : NDRC No. D95-4823 UV & THMFP Analysis Data from : FWWDLS No. AA05810-05815 FWWDLS No. AA05817-05819
	2		7.17	76		15.5								11.8	2.0	4.5	2.3	0.109		
	3		7.08	70		16.5								12.2	2.0	3.2	5.3	0.089		
	4		6.99	64		12.7								10.0	2.0	3.2	3.2	0.077	2.2	
	5		6.91	60		10.6								7.1	2.0	2.2	3.2	0.065		
	6		6.74	54		7.47								4.6	2.0	1.5	2.6	0.057	1.4	
JE-8	1	SWS-1	7.55	82		16.2	0.69						X					0.153	1.0	Arsenic & Org. C. Analysis Data from : NDRC No. D95-4896 UV & THMFP Analysis Data from : FWWDLS No. AA05842-05847 FWWDLS No. AA05849-05851
	2		7.17	75		17.0	0.49											0.111		
	3		7.08	72		15.1	0.44							12.1	2.0	3.2	3.9	0.123		
	4		6.92	65		13.5	0.30											0.067	1.1	
	5		6.80	60		11.1	0.22											0.067	1.1	
	6		6.66	52		7.47	0.20							3.3	2.0	1.5	1.0	0.058		
JE-9	1	SWS-1	6.58	51		14.6	1.08						X		2.0		3.9	0.123		Arsenic & Org. C. Analysis Data from : NDRC No. D95-4958 UV Analysis Data from : FWWDLS No. AA05871-05875
	2		6.73	51		16.6	0.81								2.0		2.2	0.102		
	3		6.60	51		17.4	0.54							12.3	2.0	3.4	2.7	0.079		
	4		6.62	51		14.7	0.25								2.0		1.0	0.069		
	5		6.55	50		15.8	0.24								2.0		1.2	0.066		
	6		6.62	53		9.66	0.26							5.8	2.0	1.5	1.1	0.061		

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B1-3 (continued)

Treatability Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process*   Job Code : *CFW9513*   Page : *2/3*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-10	*1*	*SWS-1*	*6.08*	*23*		*15.6*	*0.52*								*2.0*		*3.8*	*0.101*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-5064 UV Analysis Data from : FWWDLS No. AA05877-05882
	2		*6.06*	*22*		*18.1*	*0.34*								*2.0*		*3.4*	*0.070*		
	3		*6.07*	*22*		*19.7*	*0.21*						*X*	*11.2*	*2.0*	*3.4*	*3.3*	*0.059*		
	4		*5.96*	*20*		*13.5*	*0.19*								*2.0*		*2.8*	*0.048*		
	5		*6.05*	*24*		*8.10*	*0.17*								*2.0*		*1.0*	*0.045*		
	6		*5.99*	*22*		*3.24*	*0.14*							*1.8*	*2.0*	*11.6*	*11.3*	*0.040*		
JE-11	*1*	*SWS-1*	*5.30*	*4*		*16.3*	*0.40*							*11.3*	*2.0*	*4.3*	*4.7*	*0.064*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-5064 UV Analysis Data from : FWWDLS No. AA05883-05888
	2		*5.22*	*6*		*11.0*	*0.30*								*2.0*		*2.6*	*0.047*		
	3		*5.17*	*4*		*2.46*	*0.09*						*X*		*2.0*		*1.8*	*0.038*		
	4		*5.27*	*6*		*1.20*	*0.06*								*2.0*		*1.5*	*0.035*		
	5		*5.06*	*3*		*0.67*	*0.05*								*2.0*		*1.0*	*0.031*		
	6		*5.28*	*6*		*0.58*	*0.05*							*1.0*	*2.0*	*1.0*	*1.0*	*0.031*		
JE-12	*1*	*SWS-1*	*8.80*	*90*		*9.40*	*0.64*							*10.8*	*2.6*	*4.1*	*4.6*	*0.133*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-5234 UV & THMFP Analysis Data from : FWWDLS No. AA05907-05912 FWWDLS No. AA05914
	2		*8.35*	*87*		*5.33*	*0.46*								*2.0*		*4.0*	*0.121*		
	3		*8.13*	*84*		*4.30*	*0.38*						*X*		*2.0*		*4.0*	*0.117*		
	4		*7.67*	*82*		*4.45*	*0.34*								*2.0*		*2.3*	*0.106*		
	5		*7.43*	*77*		*4.19*	*0.27*								*2.0*		*2.2*	*0.083*		
	6		*7.30*	*74*		*3.83*	*0.18*							*3.2*	*2.0*	*1.9*	*1.0*	*0.070*	*1.0*	

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B1-3 (continued)

Treatability Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *3/3*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				III	V	ug/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-16	1	SWS-1	8.80	90	110	8.38	0.54						X	10.0	2.1	4.9	4.6	0.132		Arsenic & Org. C. Analysis Data from : NDRC No. D95-5393 UV & THMFP Analysis Data from : FWWDLS No. AA05999-06004 FWWDLS No. AA06007-06008
	2		8.75	91	114	4.86	0.45							4.6	2.6	3.0	3.7	0.122		
	3		8.60	88	122	3.94	0.43							3.0	2.0	2.5	2.6	0.114	1.0	
	4		8.56	87	124	3.67	0.28							2.6	2.0	3.6	3.4	0.107		
	5		8.69	90	133	2.93	0.27							2.3	2.0	3.7	3.7	0.108		
	6		8.46	86	137	2.49	0.17							2.0	2.0	8.5	7.3	0.094	1.9	
JE-17	1	SWS-1	9.20	60	72	12.4	0.52						X	7.5	2.7	3.0	4.4	0.120		Arsenic & Org. C. Analysis Data from : NDRC No. D95-5393 UV Analysis Data from : FWWDLS No. AA06009-06014
	2		9.21	58	80	7.81	0.25							4.0	2.0	4.5	3.7	0.111		
	3		9.18	58	82	6.28	0.23							2.0	2.0	2.8	2.8	0.105		
	4		9.14	64	92	5.46	0.15							2.0	2.0	2.4	2.3	0.104		
	5		9.31	56	92	4.33	0.12							2.0	2.0	2.9	2.0	0.099		
	6		9.31	50	90	4.58	0.13							2.0	2.0	1.8	2.4	0.095		
JE-18	1	SWS-1	6.10	24		15.3	0.21						X	11.0		6.9		0.054		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6055 UV Analysis Data from : FWWDLS No. AA06307-06312
	2		5.98	22		9.91	0.16							7.0		2.4		0.044		
	3		5.39	6		7.31	0.35							10.0		10.9		0.048		
	4		5.32	7		1.78	0.08							5.0		2.1		0.038		
	5		5.36	6		1.83	0.08							5.0		1.6		0.036		
	6		5.16	4		0.65	0.06							5.0		15.9		0.031		

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B1-4

Water Sample Quality Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Spiked Water Sample Batch Code : *SWS-2* Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*07-13-95*					*6.78*							*X*	*17.2*	*24.3*					Arsenic Analysis Data from : NDRC No. D95-6431
2	*07-18-95*	*21.9*	*7.68*	*78*		*5.56*	*0.08*	*3234*	*894*	*294*	*99.0*		*X*	*19.7*	*22.2*	*4.1*	*3.4*	*0.116*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6672 UV Analysis Data from : FWWDLS No. AA06465
3	*07-19-95*	*22.0*	*7.98*	*84*		*5.38*	*0.10*	*4115*	*957*	*196*	*21.4*		*X*							
4	*07-20-95*	*22.0*	*7.95*	*82*		*6.55*	*0.11*	*3386*	*608*	*97.1*	*16.1*		*X*							
5	*07-25-95*	*22.0*	*8.05*			*5.49*	*0.11*	*3752*	*1416*	*577*	*202*		*X*	*20.8*	*21.3*	*4.1*	*3.7*	*0.107*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6935 UV Analysis Data from : FWWDLS No. AA06526
6	*07-26-95*	*22.0*	*7.90*		*96*	*6.31*	*0.11*	*2076*	*733*	*304*	*109*		*X*							
7	*07-27-95*	*22.0*	*7.98*		*98*	*5.25*	*0.08*	*4175*	*1807*	*846*	*301*		*X*							
8	*08-07-95*	*22.5*	*8.17*	*91*		*5.67*	*0.08*	*2409*	*1006*	*398*	*108*		*X*							
9	*08-08-95*	*22.0*	*8.07*	*81*		*6.20*	*0.09*	*4409*	*1972*	*905*	*336*		*X*							
Number of Samples	-	8	8	5	2	9	8	8	8	8	8	-	-	3	3	2	2	2	-	
Average Ambient Value	-	22.1	8.0	83	97	5.91	0.10	3445	1174	452	149	-	-	19.2	22.6	4.1	3.6	0.112	-	

TABLE B1-5

Wet Chemistry Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code :** *CFW9513* **Page :** *1/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				$Fe_2(SO_4)_3$		$FeCl_3$		Alum		H_2SO_4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-19	*07-18-95*	*1*	*SWS-2*			*20*	*2.8*								
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-20	*07-18-95*	*1*	*SWS-2*	*20*	*2.1*										
		2		*40*	*4.2*										
		3		*60*	*6.3*										
		4		*80*	*8.4*										
		5		*100*	*10.5*										
		6		*120*	*12.6*										
JE-21	*07-19-95*	*1*	*SWS-2*			*20*	*2.8*			*0.550*					
		2				*40*	*5.6*			*0.425*					
		3				*60*	*8.4*			*0.300*					
		4				*80*	*11.2*			*0.200*					
		5				*100*	*14.0*			*0.100*					
		6				*120*	*16.8*								

TABLE B1-5 (continued)
Wet Chemistry Data
- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process*

Job Code : *CFW9513*

Page : *2/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				$Fe_2(SO_4)_3$		$FeCl_3$		Alum		H_2SO_4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-22	*07-19-95*	*1*	*SWS-2*			*20*	*2.8*			*1.000*					
		2				*40*	*5.6*			*0.875*					
		3				*60*	*8.4*			*0.750*					
		4				*80*	*11.2*			*0.625*					
		5				*100*	*14.0*			*0.500*					
		6				*120*	*16.8*			*0.400*					
JE-23	*07-20-95*	*1*	*SWS-2*			*20*	*2.8*			*1.450*					
		2				*40*	*5.6*			*1.300*					
		3				*60*	*8.4*			*1.150*					
		4				*80*	*11.2*			*1.000*					
		5				*100*	*14.0*			*0.850*					
		6				*120*	*16.8*			*0.700*					
JE-24	*07-20-95*	*1*	*SWS-2*	*20*	*2.1*					*1.550*					
		2		*40*	*4.2*					*1.450*					
		3		*60*	*6.3*					*1.350*					
		4		*80*	*8.4*					*1.250*					
		5		*100*	*10.5*					*1.125*					
		6		*120*	*12.6*					*1.000*					

TABLE B1-5 (continued)
Wet Chemistry Data
- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *3/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-25	*07-25-95*	*1*	*SWS-2*			*20*	*2.8*					*7.2*			
		2				*40*	*5.6*					*9.6*			
		3				*60*	*8.4*					*12.0*			
		4				*80*	*11.2*					*14.4*			
		5				*100*	*14.0*					*16.8*			
		6				*120*	*16.8*					*19.2*			
JE-26	*07-25-95*	*1*	*SWS-2*	*20*	*2.1*							*7.8*			
		2		*40*	*4.2*							*12.0*			
		3		*60*	*6.3*							*16.2*			
		4		*80*	*8.4*							*20.4*			
		5		*100*	*10.5*							*24.6*			
		6		*120*	*12.6*							*28.8*			
JE-27	*07-26-95*	*1*	*SWS-2*			*20*	*2.8*					*27.0*			
		2				*40*	*5.6*					*31.2*			
		3				*60*	*8.4*					*35.4*			
		4				*80*	*11.2*					*39.6*			
		5				*100*	*14.0*					*43.8*			
		6				*120*	*16.8*					*48.0*			

TABLE B1-5 (continued)

Wet Chemistry Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *4/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-28	*07-28-95*	*1*	*SWS-2*			*20*	*2.8*					*81.0*			
		2				*40*	*5.6*					*85.8*			
		3				*60*	*8.4*					*90.6*			
		4				*80*	*11.2*					*95.4*			
		5				*100*	*14.0*					*100.2*			
		6				*120*	*16.8*					*105.0*			
JE-29	*08-07-95*	*1*	*SWS-2*					*40*	*1.68*						
		2						*80*	*3.36*						
		3						*120*	*5.04*						
		4						*160*	*6.72*						
		5						*200*	*8.40*						
		6						*240*	*10.08*						
JE-30	*08-08-95*	*1*	*SWS-2*					*40*	*1.68*	*1.375*					
		2						*80*	*3.36*	*1.200*					
		3						*120*	*5.04*	*1.025*					
		4						*160*	*6.72*	*0.850*					
		5						*200*	*8.40*	*0.675*					
		6						*240*	*10.08*	*0.500*					

TABLE B1-6
Treatability Data
- Coagulation Diagram Experiment -

Project : Arsenic Removal in Water Treatment Process
Job Code : CFW9513
Page : 1/4

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-19	1	SWS-2	7.07	71		2.58	0.08	598	114	21.2	2.88		X	9.1	4.8	3.0	3.8	0.096		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6679 UV Analysis Data from : FWWDLS No. AA86459-86464
	2		6.77	64		0.90	0.07	612	128	22.4	3.92			3.6		2.9		0.075		
	3		6.48	58		0.60	0.08	278	71.4	16.5	3.14			2.0	3.3	3.5	3.0	0.059		
	4		6.33	50		0.37	0.09	154	36.5	8.56	1.85			1.5		1.9		0.049		
	5		6.14	44		0.20	0.08	81.1	21.3	4.28	0.76			1.1		1.0		0.046		
	6		6.02	36		0.16	0.07	159	40.2	9.12	1.44			1.0	3.5	1.0	1.0	0.039		
JE-20	1	SWS-2	7.13	73		3.79	0.48	3445	887	204	27.9		X	21.5	5.0	3.3	3.6	0.099		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6684 UV Analysis Data from : FWWDLS No. AA86466-86471
	2		6.90	66		4.58	0.55	1882	435	91.4	10.2			15.7		2.5		0.087		
	3		6.60	62		4.59	0.08	2102	376	43.6	3.61			15.9	5.0	2.7	2.9	0.071		
	4		6.49	55		4.57	0.09	2641	349	25.8	3.25			9.8		4.9		0.063		
	5		6.39	50		2.70	0.07	1027	164	27.0	3.60			4.2		4.3		0.053		
	6		6.26	45		2.75	0.07	835	119	17.2	3.34			4.3	5.0	4.4	2.2	0.048		
JE-21	1	SWS-2	6.63	47		2.96	0.58	2956	604	116	13.3		X	18.4	4.9	5.9	3.7	0.087		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6685 UV Analysis Data from : FWWDLS No. AA86475-86480
	2		6.65	45		1.43	0.38	249	45.2	11.7	1.76			8.2		4.6		0.069		
	3		6.60	46		0.63	0.12	116	25.8	6.13	0.32			2.7	2.9	4.5	2.7	0.059		
	4		6.53	46		0.32	0.08	91.3	24.7	6.60	0.71			1.2		3.6		0.048		
	5		6.53	42		0.20	0.06	67.1	13.6	2.60	0.29			1.0		3.2		0.042		
	6		6.51	42		0.17	0.08	44.2	9.69	2.45	0.25			1.0	2.7	5.9	5.1	0.038		

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B1-6 (continued)

Treatability Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process*

Job Code : *CFW9513*

Page : *2/4*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Spiked with		Arsenic		Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 µm	5 µm	10 µm	20 µm	III	V	Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cmul. No./mL						mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-22	*1*	*SWS-2*	*6.19*	*26*		*4.18*		*3287*	*585*	*90.7*	*6.43*		*X*	*18.8*	*5.3*	*9.7*	*6.4*	*0.070*		**Arsenic & Org. C. Analysis Data from :** **NDRC No. D95-6686** **UV Analysis Data from :** **FWWDLS No. AA06481-06486**
	2		*6.20*	*32*		*5.24*		*1487*	*227*	*29.1*	*1.95*			*16.8*		*5.4*		*0.057*		
	3		*6.17*	*26*		*1.51*	*0.22*	*136*	*23.4*	*5.80*	*0.68*			*4.7*	*2.3*	*4.1*	*1.8*	*0.046*		
	4		*6.20*	*24*		*0.53*	*0.10*	*47.5*	*10.0*	*2.33*	*0.20*			*1.0*		*4.1*		*0.038*		
	5		*6.14*	*22*		*0.34*	*0.10*	*30.6*	*6.49*	*1.83*	*0.13*			*1.0*		*4.3*		*0.036*		
	6		*6.14*	*24*		*0.22*	*0.06*	*54.2*	*9.65*	*2.35*	*0.33*			*1.0*	*2.6*	*11.6*	*6.7*	*0.033*		
JE-23	*1*	*SWS-2*	*5.39*	*6*		*3.95*	*0.08*	*2301*	*459*	*84.8*	*10.0*		*X*	*20.3*	*1.6*	*13.1*	*10.6*			**Arsenic & Org. C. Analysis Data from :** **NDRC No. D95-6737** **UV Analysis Data from :** **FWWDLS No. AA06497-06500**
	2		*5.46*	*6*		*1.21*	*0.08*	*41.5*	*11.1*	*3.08*	*0.21*			*5.5*		*4.6*		*0.032*		
	3		*5.52*	*6*		*0.42*	*0.07*	*15.3*	*4.76*	*1.45*	*0.07*			*2.2*	*1.0*	*2.8*	*2.8*	*0.028*		
	4		*5.64*	*8*		*0.45*	*0.06*	*21.1*	*6.99*	*1.80*	*0.19*			*1.6*		*2.5*				
	5		*5.40*	*6*		*0.41*	*0.05*	*19.7*	*6.82*	*2.40*	*0.30*			*1.5*		*2.3*		*0.024*		
	6		*5.52*	*8*		*0.34*	*0.06*	*51.3*	*17.0*	*4.27*	*0.65*			*1.6*	*1.0*	*17.8*	*16.3*	*0.022*		
JE-24	*1*	*SWS-2*	*4.78*			*3.99*	*0.10*	*2807*	*580*	*114*	*20.7*		*X*	*22.0*	*2.9*	*10.0*	*6.7*			**Arsenic & Org. C. Analysis Data from :** **NDRC No. D95-6731**
	2		*4.64*			*1.32*	*0.26*	*58*	*12.8*	*3.97*	*0.57*			*4.8*		*5.8*				
	3		*4.58*			*0.94*	*0.13*	*55*	*15.5*	*5.74*	*0.28*			*2.1*	*1.0*	*6.2*	*4.7*			
	4		*4.59*			*0.59*	*0.08*	*33*	*9.08*	*3.01*	*0.24*			*2.8*		*3.3*				
	5		*4.60*			*0.75*	*0.09*	*27*	*7.64*	*2.55*	*0.28*			*2.1*		*3.1*				
	6		*4.27*			*0.73*	*0.06*	*44*	*13.5*	*4.30*	*0.48*			*2.0*	*1.0*	*10.3*	*7.3*			

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B1-6 (continued)

Treatability Data

- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process*

Job Code : *CFW9513*

Page : *3/4*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 µm	5 µm	10 µm	20 µm	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-25	*1*	*SWS-2*	*8.40*	*82*		*0.37*	*0.06*	*196*	*59.9*	*6.00*	*0.32*		*X*	*5.7*	*5.3*	*4.8*	*4.9*	*0.098*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6935 UV Analysis Data from : FWWDLS No. AA06514-06519
	2		*8.11*	*81*		*0.25*	*0.08*	*98.4*	*48.8*	*5.12*	*0.60*			*2.1*		*4.1*		*0.088*		
	3		*7.66*	*76*		*0.23*	*0.08*	*87.3*	*46.5*	*3.96*	*0.40*			*1.7*	*2.4*	*4.1*	*2.2*	*0.072*		
	4		*7.57*	*73*		*0.22*	*0.07*	*58.2*	*35.7*	*2.44*	*0.18*			*1.1*		*3.2*		*0.064*		
	5		*7.47*	*70*		*0.31*	*0.06*	*54.6*	*30.7*	*1.94*	*0.28*			*1.0*		*2.8*		*0.058*		
	6		*7.44*	*64*		*0.26*	*0.06*	*23.8*	*6.36*	*1.66*	*0.20*			*1.0*	*2.1*	*6.2*	*4.7*	*0.058*		
JE-26	*1*	*SWS-2*	*8.60*	*85*		*2.50*	*0.17*	*2916*	*741*	*106*	*10.8*		*X*	*12.8*	*5.2*	*4.7*	*4.0*	*0.109*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6935 UV Analysis Data from : FWWDLS No. AA06520-06525
	2		*8.61*	*85*		*1.69*	*0.17*	*412*	*105*	*18.4*	*2.82*			*5.3*		*4.9*		*0.098*		
	3		*8.62*	*86*		*1.19*	*0.18*	*142*	*55.5*	*7.02*	*0.80*			*3.4*	*2.7*	*4.2*	*2.9*	*0.093*		
	4		*8.60*	*84*		*0.86*	*0.08*	*120*	*54.6*	*6.28*	*0.94*			*2.3*		*3.8*		*0.090*		
	5		*8.61*	*83*		*1.45*	*0.06*	*93.0*	*40.7*	*4.26*	*0.42*			*2.0*		*3.7*		*0.087*		
	6		*8.60*	*82*		*1.12*	*0.07*	*159*	*65.4*	*11.27*	*1.95*			*1.5*	*2.6*	*3.7*	*3.0*	*0.086*		
JE-27	*1*	*SWS-2*	*9.32*	*76*	*96*	*0.77*	*0.15*	*4155*	*1252*	*104*	*6.74*		*X*	*6.4*	*7.2*	*4.5*	*3.2*	*0.054*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6935 UV Analysis Data from : FWWDLS No. AA06528-06533
	2		*9.27*	*74*	*100*	*0.60*		*2325*	*563*	*10.6*	*0.64*			*3.3*		*4.0*		*0.044*		
	3		*9.09*	*77*	*108*	*0.36*		*159*	*32.9*	*2.96*	*0.38*			*2.0*	*4.9*	*3.8*	*4.0*	*0.048*		
	4		*9.11*	*72*	*110*	*0.27*	*0.17*	*124*	*22.6*	*2.55*	*0.33*			*1.1*		*3.1*		*0.038*		
	5		*9.08*	*69*	*118*	*0.22*	*0.12*	*275*	*24.2*	*2.96*	*0.26*			*1.0*		*4.1*		*0.036*		
	6		*9.01*	*68*	*118*	*0.21*	*0.07*	*91.2*	*13.5*	*1.78*	*0.14*			*1.0*	*3.5*	*3.7*	*3.0*	*0.031*		

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B1-6 (continued)
Treatability Data
- Coagulation Diagram Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *4/4*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 µm	5 µm	10 µm	20 µm	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-28	*1*	*SWS-2*	*10.63*	*47*	*64*	*1.07*	*0.08*	*6421*	*1198*	*73.7*	*2.10*		*X*	*3.8*	*5.8*	*5.4*	*3.9*	*0.073*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-6935 UV Analysis Data from : FWWDLS No. AA06534-06539
	2		*10.65*	*45*	*70*	*0.42*	*0.10*	*2550*	*188*	*2.72*	*0.18*			*2.1*		*3.7*		*0.069*		
	3		*10.61*	*39*	*70*	*0.39*	*0.06*	*82.5*	*7.48*	*1.62*	*0.22*			*1.1*	*4.4*	*3.9*	*3.0*	*0.064*		
	4		*10.65*	*35*	*74*	*0.36*	*0.06*	*32.0*	*6.54*	*1.42*	*0.12*			*1.0*		*3.0*		*0.059*		
	5		*10.61*	*32*	*78*	*0.45*	*0.06*	*89.5*	*14.4*	*4.02*	*0.44*			*1.0*		*2.6*		*0.057*		
	6		*10.59*	*34*	*82*	*0.50*	*0.08*	*39.2*	*6.09*	*1.41*	*0.19*			*1.0*	*5.5*	*4.8*	*3.8*	*0.055*		
JE-29	*1*	*SWS-2*	*7.25*	*73*		*0.79*	*0.10*	*339*	*102*	*33.6*	*7.72*		*X*	*10.6*	*5.3*	*4.3*	*3.8*	*0.083*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-7303 UV Analysis Data from : FWWDLS No. AA06608-06613
	2		*6.87*	*63*		*0.41*	*0.05*	*146*	*50.2*	*19.0*	*3.93*			*2.9*		*4.2*		*0.059*		
	3		*6.77*	*54*		*0.39*	*0.05*	*91.4*	*35.4*	*12.3*	*2.48*			*1.9*	*2.0*	*3.7*	*5.1*	*0.049*		
	4		*6.50*	*45*		*0.43*	*0.06*	*85.8*	*31.3*	*10.6*	*1.56*			*1.2*		*2.7*		*0.043*		
	5		*6.31*	*38*		*0.38*	*0.05*	*114*	*41.0*	*14.5*	*2.38*			*1.2*		*2.4*		*0.038*		
	6		*6.14*	*26*		*0.33*	*0.05*	*132*	*48.0*	*19.1*	*3.48*			*2.2*	*2.0*	*4.2*	*3.8*	*0.037*		
JE-30	*1*	*SWS-2*	*5.55*	*9*		*0.56*	*0.06*	*328*	*122*	*26.3*	*2.44*		*X*	*4.9*	*2.0*	*5.6*	*5.1*	*0.046*		Arsenic & Org. C. Analysis Data from : NDRC No. D95-7303 UV Analysis Data from : FWWDLS No. AA06625-06630
	2		*5.40*	*6*		*0.44*	*0.05*	*206*	*73.2*	*13.6*	*1.02*			*1.7*		*3.0*		*0.037*		
	3		*5.43*	*8*		*0.48*	*0.06*	*247*	*71.0*	*13.3*	*1.28*			*2.0*	*2.0*	*2.1*	*1.6*	*0.036*		
	4		*5.50*	*9*		*0.93*	*0.08*	*209*	*64.7*	*19.5*	*3.00*			*2.4*		*1.8*		*0.034*		
	5		*5.46*	*7*		*0.87*	*0.08*	*176*	*47.0*	*14.4*	*2.08*			*1.9*		*2.5*		*0.033*		
	6		*5.59*	*8*		*0.82*	*0.09*	*238*	*61.3*	*19.3*	*3.46*			*1.3*	*2.0*	*13.6*	*13.3*	*0.033*		

Note: When the measurement is lower than the detection limit, the detection limit for that analysis is used as the result (underlined value).

APPENDIX B2

EXPERIMENTAL DATA SHEETS
FOR PREOZONATION EXPERIMENTS

TABLES

TABLE B2-1
Water Sample Quality Data
- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Spiked Water Sample Batch Code : *SWS-4* Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 µm	5 µm	10 µm	20 µm	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*11-09-95*	*18.5*	*8.10*	*92*		*10.3*						*X*		*30.0*	*37.7*					Arsenic Analysis Data from : NDRC No. D95-11026
Number of Samples	-	*1*	*1*	*1*	-	*1*	-	-	-	-	-	-	-	*1*	*1*	-	-	-	-	
Average Ambient Value	-	*18.5*	*8.1*	*92*	-	*10.30*	-	-	-	-	-	-	-	*30.0*	*37.7*	-	-	-	-	

TABLE B2-2
Wet Chemistry Data
- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code** *CFW9513* **Page :** *1/1*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Dose	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
JE-37	*11-09-95*	*1*	*SWS-4*			*20*	*2.8*								
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								

TABLE B2-3
Treatability Data
- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process*

Job Code : *CFW9513*

Page : *1/1*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Settled	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-37	*1*	*SWS-4*	*7.50*			*1.93*						*X*		*26.4*						Arsenic & Org. C. Analysis Data from : NDRC No. D95-11826
	2		*7.24*			*1.16*								*16.4*						
	3		*7.10*			*1.12*								*13.2*						
	4		*7.00*			*0.54*								*10.8*						
	5		*6.88*			*0.30*								*8.6*						
	6		*6.85*			*0.36*								*7.2*						

TABLE B2-4

Water Sample Quality Data

- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Spiked Water Sample Batch Code : *SWS-6-1* Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*04-25-96*	*18.9*	*7.83*	*106*		*13.2*							*X*	*22.9*						Arsenic Analysis Data from : **NDRC No. D96-4428**
2	*04-25-96*												*X*	*18.8*						
Number of Samples	-	*1*	*1*	*1*	-	*1*	-	-	-	-	-	-	-	*2*	-	-	-	-	-	
Average Ambient Value	-	*18.9*	*7.8*	*106*	-	*13.2*	-	-	-	-	-	-	-	*20.9*	-	-	-	-	-	

TABLE B2-5

Water Sample Quality Data

- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process*   Job Code : *CFW9513*   Spiked Water Sample Batch Code : *SWS-6-2*   Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 µm	5 µm	10 µm	20 µm	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	µg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*05-01-96*	*19.5*	*8.03*	*112*		*11.4*						*X*		*13.2*						Arsenic Analysis Data from : NDRC No. D96-4768
2	*05-02-96*	*19.6*	*7.91*	*110*		*11.2*						*X*		*14.2*						Arsenic Analysis Data from : NDRC No. D96-4769
3	*05-02-96*											*X*		*13.8*						
Number of Samples	-	*2*	*2*	*2*	-	*2*	-	-	-	-	-	-	-	-	-	-	-	-	-	
Average Ambient Value	-	*19.6*	*8.0*	*111*	-	*11.3*	-	-	-	-	-	-	-	*13.7*	-	-	-	-	-	

TABLE B2-6

Water Sample Quality Data

- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process*
Job Code : *CFW9513*
Spiked Water Sample Batch Code : *SWS-6-3*
Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	05-10-96	21.5	7.90	104		9.72						X		10.1						Arsenic Analysis Data from : NDRC No. D96-5209
2	05-10-96											X		10.9						
Number of Samples	-	1	1	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	
Average Ambient Value	-	21.5	7.9	104	-	9.72	-	-	-	-	-	-	-	10.5	-	-	-	-	-	

TABLE B2-7
Wet Chemistry Data
- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code** *CFW9513* **Page :** *1/2*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-51	*04-25-96*	*1*	*SWS-6-1*			*20*	*2.8*							*9*	
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-52	*05-01-96*	*1*	*SWS-6-2*			*20*	*2.8*							*9*	
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-53	*05-02-96*	*1*	*SWS-6-2*			*20*	*2.8*							*9*	
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								

TABLE B2-7 (continued)

Wet Chemistry Data

- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code** *CFW9513* **Page :** *2/2*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				$Fe_2(SO_4)_3$		$FeCl_3$		Alum		H_2SO_4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-54	05-02-96	1	SWS-6-2	20	2.1									9	
		2		40	4.2										
		3		60	6.3										
		4		80	8.4										
		5		100	10.5										
		6		120	12.6										
JE-55	05-10-96	1	SWS-6-3			20	2.8								
		2				40	5.6								
		3				60	8.4								
		4				80	11.2								
		5				100	14.0								
		6				120	16.8								
JE-56	05-10-96	1	SWS-6-3	20	2.1										
		2		40	4.2										
		3		60	6.3										
		4		80	8.4										
		5		100	10.5										
		6		120	12.6										

TABLE B2-8
Treatability Data
- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *1/2*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Remark
						Settled	Filtered	Settled 2 um	5 um	10 um	20 um	Spiked with III	V	Total	Dissolved	
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL						ug/L		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
JE-51	*1*	*SWS-6-1*	*7.33*	*104*		*0.95*							*X*	*4.2*		Arsenic Analysis Data from : NDRC No. D96-4428
	2		*7.06*	*96*		*0.47*								*3.0*		
	3		*6.96*	*88*		*0.40*								*2.2*		
	4		*6.80*	*78*		*0.19*								*1.4*		
	5		*6.75*	*72*		*0.19*								*1.0*		
	6		*6.70*	*64*		*0.21*								*1.1*		
JE-52	*1*	*SWS-6-2*	*7.30*			*1.52*						*X*		*3.5*		Arsenic Analysis Data from : NDRC No. D96-4768
	2		*7.16*			*0.98*								*2.2*		
	3		*7.00*	*90*		*0.49*								*1.6*		
	4		*6.87*	*82*		*0.25*								*1.7*		
	5		*6.72*	*76*		*0.22*								*1.0*		
	6		*6.65*	*68*		*0.21*								*1.5*		
JE-53	*1*	*SWS-6-2*	*7.13*	*102*		*2.27*						*X*		*2.7*		Arsenic Analysis Data from : NDRC No. D96-4769
	2		*7.00*	*98*		*1.51*								*1.6*		
	3		*6.80*	*84*		*1.02*								*1.0*		
	4		*6.70*	*80*		*0.74*								*1.5*		
	5		*6.65*	*68*		*0.44*								*1.0*		
	6		*6.58*	*62*		*0.37*								*1.0*		

Note: When the measurement is lower than detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B2-8 (continued)
Treatability Data
- Preozonation Experiment -

Project : *Arsenic Removal in Water Treatment Process*　　Job Code : *CFW9513*　　Page : *2/2*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Remark
						Settled	Filtered	Settled				Spiked with		Total	Dissolved	
								2 um	5 um	10 um	20 um	III	V			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL						ug/L		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
JE-54	*1*	*SWS-6-2*	*7.42*	*103*		*5.85*						*X*		*12.4*		Arsenic Analysis Data from : NDRC No. D96-4769
	2		*7.27*	*92*		*3.85*								*7.5*		
	3		*7.19*	*90*		*3.47*								*5.3*		
	4		*7.08*	*84*		*2.77*								*4.2*		
	5		*7.04*	*82*		*1.84*								*1.8*		
	6		*6.99*	*80*		*1.86*								*1.5*		
JE-55	*1*	*SWS-6-3*	*7.28*	*98*		*2.30*						*X*		*6.2*		Arsenic Analysis Data from : NDRC No. D96-5209
	2		*7.14*	*92*		*1.37*								*4.4*		
	3		*7.08*	*84*		*0.77*								*3.7*		
	4		*6.98*	*76*		*0.48*								*2.6*		
	5		*6.89*	*68*		*0.46*								*1.9*		
	6		*6.83*	*64*		*0.42*								*2.3*		
JE-56	*1*	*SWS-6-3*	*7.35*	*98*		*5.18*						*X*		*6.2*		Arsenic Analysis Data from : NDRC No. D96-5209
	2		*7.28*	*94*		*3.28*								*4.7*		
	3		*7.22*	*88*		*2.63*								*4.9*		
	4		*7.14*	*84*		*2.37*								*4.0*		
	5		*7.06*	*76*		*2.21*								*4.0*		
	6		*7.00*	*72*		*1.63*								*3.9*		

Note: When the measurement is lower than detection limit, the detection limit for that analysis is used as the result (underlined value).

APPENDIX B3

EXPERIMENTAL DATA SHEETS
FOR RSLUDGE PRODUCTION EXPERIMENTS

TABLES

Experiments with Water Sample SWS-3:

TABLE B3-1
Water Sample Quality Data
- Sludge Production Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code :** *CFW9513* **Spiked Water Sample Batch Code :** *SWS-3* **Page :** *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Turbidity		Particle Count				Suspended Solids	Iron		Aluminum		Remark
					Original	Filtered	2 um	5 um	10 um	20 um		Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU		Cuml. No./mL				mg/L	mg/L		mg/L		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	09-26-95	22.0	7.80	83	4.57		6555	1288	265	84	7.33	2.274	0.735	0.570	0.007	Metal Analysis Data from : FWWDLS No. AA07061
2	09-28-95	25.0	7.79	83	5.13		8756	1953	446	129	7.38	2.344	0.913	0.462	0.021	Metal Analysis Data from : FWWDLS No. AA07071
3	10-03-95	22.0	7.94	84	5.28		9129	2949	881	227	8.15	0.897	0.733	0.125	0.002	Metal Analysis Data from : FWWDLS No. AA07109
4	10-05-95	21.5	7.90	84	5.33		7567	2659	881	238	9.85	2.670	0.568	0.242	0.005	Metal Analysis Data from : FWWDLS No. AA07139
5	10-10-95	21.0	7.83	84	5.56		5727	2001	517	50.8	10.16			0.198	0.008	Metal Analysis Data from : FWWDLS No. AA07180
6	10-12-95	21.5	7.78	84	6.34		5757	2514	1039	331	9.90					
Number of Samples	-	6	6	6	6	-	6	6	6	6	6	4	4	5	5	
Average Ambient Value	-	22.2	7.84	83.7	5.37	-	7249	2227	671	176	8.79	2.046	0.737	0.319	0.009	

TABLE B3-2
Wet chemistry Data
- Sludge Production Experiment -

Project : *Arsenic Removal in Water Treatment Process*

Job Code : *CFW9513*

Page : *1/2*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-31	*09-26-95*	*1*	*SWS-3*			*80*	*11.2*			*0.625*					
		2				*80*	*11.2*			*1.250*					
		3				*120*	*16.8*			*0.400*					
		4				*120*	*16.8*			*0.800*					
		5													
		6													
JE-32	*09-28-95*	*1*	*SWS-3*			*80*	*11.2*								
		2				*80*	*11.2*			*1.100*					
		3				*120*	*16.8*								
		4				*120*	*16.8*			*0.900*					
		5													
		6													
JE-33	*10-03-95*	*1*	*SWS-3*			*40*	*5.6*								
		2				*40*	*5.6*			*0.450*					
		3				*40*	*5.6*			*0.950*					
		4				*40*	*5.6*			*1.350*					
		5													
		6													

TABLE B3-2 (continued)

Wet chemistry Data

- Sludge Production Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *2/2*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-34	*10-05-95*	*1*	*SWS-3*			*20*	*2.8*								
		2				*20*	*2.8*			*0.600*					
		3				*20*	*2.8*			*1.100*					
		4				*20*	*2.8*			*1.500*					
		5													
		6													
JE-35	*10-10-95*	*1*	*SWS-3*	*80*	*8.4*					*0.250*					
		2		*80*	*8.4*					*1.300*					
		3		*120*	*12.6*										
		4		*120*	*12.6*					*1.000*					
		5													
		6													
JE-36	*10-12-95*	*1*	*SWS-3*	*20*	*2.1*					*0.625*					
		2		*20*	*2.1*					*1.650*					
		3		*40*	*4.2*					*0.500*					
		4		*40*	*4.2*					*1.550*					
		5													
		6													

TABLE B3-3

Treatability Data

- Sludge Production Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code :** *CFW9513* **Page :** *1/2*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Remark
						Settled	Filtered	2 um	5 um	10 um	20 um	
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				
1	2	3	4	5	6	7	8	9	10	11	12	13
JE-31	*1*	*SWS-3*	*6.26*	*26*		*0.49*		*164*	*53.0*	*11.4*	*1.14*	
	2		*4.40*			*0.67*		*265*	*92.4*	*23.4*	*2.70*	
	3		*6.23*	*24*		*0.26*		*154*	*50.2*	*13.2*	*1.00*	
	4		*5.56*	*7*		*0.39*		*162*	*37.8*	*8.69*	*1.02*	
	5											
	6											
JE-32	*1*	*SWS-3*	*6.92*	*57*		*0.18*		*147*	*40.7*	*8.56*	*0.98*	
	2		*5.46*	*6*		*0.47*		*141*	*43.5*	*11.4*	*1.30*	
	3		*6.71*	*42*		*0.13*		*148*	*46.6*	*10.0*	*0.92*	
	4		*5.11*	*4*		*0.36*		*121*	*43.3*	*8.00*	*0.64*	
	5											
	6											
JE-33	*1*	*SWS-3*	*7.22*	*70*		*0.28*		*165*	*40.5*	*7.36*	*1.18*	
	2		*6.60*	*50*		*0.45*		*232*	*58.4*	*11.2*	*1.64*	
	3		*6.27*	*24*		*2.41*		*339*	*76.0*	*17.1*	*2.82*	
	4		*5.24*	*4*		*2.06*		*202*	*26.5*	*5.42*	*1.06*	
	5											
	6											

TABLE B3-3 (continued)

Treatability Data

- Sludge Production Experiment -

Project : *Arsenic Removal in Water Treatment Process*

Job Code : *CFW9513*

Page : *2/2*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Remark
						Settled	Filtered	2 um	5 um	10 um	20 um	
				mg/L as CaCO3	mg/L as CaCO3	NTU		Avg. Cuml. No./mL				
1	2	3	4	5	6	7	8	9	10	11	12	13
JE-34	*1*	*SWS-3*	*7.37*	*78*		*0.38*		*245*	*89.5*	*17.4*	*3.14*	
	2		*6.68*	*48*		*1.85*		*1186*	*320*	*81.6*	*16.2*	
	3		*6.17*	*24*		*3.96*		*4192*	*1184*	*284*	*42.8*	
	4		*5.35*	*6*		*2.41*		*744*	*153*	*29.5*	*4.80*	
	5											
	6											
JE-35	*1*	*SWS-3*	*6.78*	*54*		*2.04*		*241*	*52.7*	*15.0*	*4.32*	
	2		*5.02*	*2*		*0.55*		*45.1*	*13.7*	*4.28*	*0.80*	
	3		*6.85*	*53*		*1.08*		*126*	*35.9*	*8.26*	*1.58*	
	4		*5.50*	*7*		*0.57*		*57.9*	*23.0*	*7.98*	*1.64*	
	5											
	6											
JE-36	*1*	*SWS-3*	*6.64*	*50*		*3.06*		*3072*	*1004*	*282*	*46.7*	
	2		*4.40*			*0.95*		*401*	*89.2*	*18.9*	*2.68*	
	3		*6.68*	*50*		*5.01*		*2210*	*636*	*147*	*19.6*	
	4		*4.00*			*1.70*		*274*	*35.0*	*6.28*	*0.72*	
	5											
	6											

TABLE B3-4
Mass Balance Data
- Sludge Production Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : *1/2*

Test Code	Jar Code	Spiked Water Sample Code	Suspended Solids		Sludge Volume	Iron				Remark
			Settled Water	Sludge		Settled Water		Sludge		
						Total	Dissolved	Total	Dissolved	
			mg/L @ 2-L Jar		mL @2-L Jar	mg/L @ 2-L Jar				
1	2	3	4	5	6	7	8	9	10	11
JE-31	*1*	*SWS-3*	*1.30*	*25.93*	*18.0*	*1.908*	*0.821*	*9.088*		Metal Analysis Data from : FWWDLS No. AA07062-07069
	2		*0.73*	*26.44*	*17.0*	*1.726*	*0.675*	*9.173*		
	3		*0.60*	*35.68*	*22.0*	*1.393*	*0.795*	*13.438*		
	4		*0.41*	*36.53*	*21.0*	*1.760*	*0.683*	*14.360*		
	5									
	6									
JE-32	*1*	*SWS-3*	*0.43*	*27.49*	*22.0*	*1.224*	*0.555*	*9.279*		Metal Analysis Data from : FWWDLS No. AA07072-07079
	2		*0.50*	*26.98*	*17.0*	*1.353*	*0.907*	*8.858*		
	3		*0.14*	*37.86*	*27.0*	*1.153*	*0.742*	*14.039*		
	4		*0.54*	*36.36*	*18.5*	*1.306*	*1.205*	*13.772*		
	5									
	6									
JE-33	*1*	*SWS-3*	*1.32*	*19.50*	*13.0*	*0.954*	*0.760*	*5.283*		Metal Analysis Data from : FWWDLS No. AA07110-07117
	2		*1.60*	*18.97*	*9.0*	*1.110*	*0.763*	*4.867*		
	3		*4.57*	*14.65*	*6.5*	*2.590*	*0.755*	*3.338*		
	4		*3.53*	*15.73*	*6.0*	*1.730*	*0.735*	*4.187*		
	5									
	6									

TABLE B3-4 (continued)

Mass Balance Data

- Sludge Production Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Page : 2/2

Test Code	Jar Code	Spiked Water Sample Code	Suspended Solids		Sludge Volume	Iron				Remark
			Settled Water	Sludge		Settled Water		Sludge		
						Total	Dissolved	Total	Dissolved	
			mg/L @ 2-L Jar		mL @2-L Jar	mg/L @ 2-L Jar				
1	2	3	4	5	6	7	8	9	10	11
JE-34	*1*	*SWS-3*	*1.75*	*11.38*	*6.0*	*1.430*	*0.567*	*2.498*		**Metal Analysis Data from :** **FWWDLS No. AA07140-07147**
	2		*4.09*	*8.98*	*1.8*	*2.310*	*0.632*	*1.115*		
	3		*7.56*	*5.51*	*0.8*	*3.190*	*0.768*	*0.333*		
	4		*4.04*	*9.41*	*2.5*	*2.200*	*0.745*	*1.249*		
	5									
	6									
JE-35	*1*	*SWS-3*	*3.22*	*9.76*	*8.0*	*1.626*	*0.841*	*5.779*		**Metal Analysis Data from :** **FWWDLS No. AA07181-07188**
	2		*0.93*	*11.13*	*14.0*	*0.736*	*0.589*	*6.690*		
	3		*1.86*	*13.83*	*14.5*	*1.033*	*0.706*	*11.133*		
	4		*0.75*	*14.32*	*15.5*	*0.830*	*0.741*	*11.785*		
	5									
	6									
JE-36	*1*	*SWS-3*	*3.87*		*0.5*					
	2		*1.55*	*10.01*	*3.0*					
	3		*7.46*	*7.56*	*0.9*					
	4		*2.02*	*12.57*	*7.5*					
	5									
	6									

APPENDIX B4

EXPERIMENTAL DATA SHEETS

FOR ARSENIC REMOVAL MECHANISM EXPERIMENTS

TABLES

<u>Experiments with Water Sample SWS-5:</u>

TABLE B4-1

Water Sample Quality Data

- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Spiked Water Sample Batch Code : *SWS-5* Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cumul. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*01-29-96*												*X*	*94.0*	*92.5*					Arsenic Analysis Data from : NDRC No. D96-273
2	*01-29-96*												*X*	*95.6*	*91.6*					Arsenic Analysis Data from : NDRC No. D96-273
Number of Samples	-	-	-	-	-	-	-	-	-	-	-	-	-	*2*	*2*	-	-	-	-	
Average Ambient Value	-	-		-	-	-	-	-	-	-	-	-	-	*94.8*	*92.1*	-	-	-	-	

TABLE B4-2
Water Sample Quality Data
- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Spiked Water Sample Batch Code : *SWS-5-1* Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 um	5 um	10 um	20 um	Spiked with III	Spiked with V	Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL						mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	02-19-96	18.0	8.05	102		0.22		328	59.3	14.1	0.86		X							
2	02-21-96	18.6	8.10			0.24							X							
Number of Samples	-	2	2	1	-	2	-	1	1	1	1	-	-	-	-	-	-	-	-	
Average Ambient Value	-	18.3	8.1	102	-	0.23	-	328	59.3	14.1	0.86	-	-	(94.8)	(92.1)	-	-	-	-	

Note: Arsenic Concentrations (parenthesized values) are the as same as that in SWS-5.

TABLE B4-3
Water Sample Quality Data
- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process*   Job Code : *CFW9513*   Spiked Water Sample Batch Code : *SWS-5-2*   Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	µg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	02-26-96	17.5	8.07			0.23							X							
2	02-27-96	18.0	8.01			0.24							X							
Number of Samples	-	2	2	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	
Average Ambient Value	-	17.8	8.0	-	-	0.24	-	-	-	-	-	-	-	(47.4)	(46.0)	-	-	-	-	

Note: Arsenic Concentrations (parenthesized values) are calculated on the basis of that in SWS-5.

TABLE B4-4

Water Sample Quality Data

- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process*   Job Code : *CFW9513*   Spiked Water Sample Batch Code : *SWS-5-3*   Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 µm	5 µm	10 µm	20 µm	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	µg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*03-12-96*	*18.0*	*8.10*	*113*		*0.23*							*X*							
Number of Samples	-	*1*	*1*	*1*	-	*1*	-	-	-	-	-	-	-	-	-	-	-	-	-	
Average Ambient Value	-	*18.0*	*8.1*	*113*	-	*0.23*	-	-	-	-	-	-	-	*(23.7)*	*(23.0)*	-	-	-	-	

Note: Arsenic Concentrations (parenthesized values) are calculated on the basis of that in SWS-5.

TABLE B4-5

Water Sample Quality Data

- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code : *CFW9513* Spiked Water Sample Batch Code : *SWS-5-4* Page : *1/1*

Sample No.	Sampling Date	Temperature	pH	Total Alkalinity	Total Hardness	Turbidity		Particle Count				Arsenic				Organic Carbon		UV 254	Total THMFP	Remark
						Original	Filtered	2 um	5 um	10 um	20 um	Spiked with		Total	Dissolved	Total	Dissolved			
				mg/L as CaCO3	mg/L as CaCO3	NTU		Cuml. No./mL				III	V	mg/L		mg/L		1/cm	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	*03-13-96*	*18.0*	*8.12*			*0.25*							*X*							
Number of Samples	-	*1*	*1*	-	-	*1*	-	-	-	-	-	-	-	-	-	-	-	-	-	
Average Ambient Value	-	*18.0*	*8.1*	-	-	*0.25*	-	-	-	-	-	-	-	*(11.9)*	*(11.5)*	-	-	-	-	

Note: Arsenic Concentrations (parenthesized values) are calculated on the basis of that in SWS-5.

TABLE B4-6

Wet Chemistry Data

- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code *CFW9513* Page : *1/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				$Fe_2(SO_4)_3$		$FeCl_3$		Alum		H_2SO_4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-39	*02-19-96*	*1*	*SWS-5-1*			*20*	*2.8*								
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-40	*02-19-96*	*1*	*SWS-5-1*			*20*	*2.8*						*40*		
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-41	*02-20-96*	*1*	*SWS-5-1*			*20*	*2.8*						*10*		
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								

TABLE B4-6 (continued)
Wet Chemistry Data
- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process* **Job Code** *CFW9513* **Page :** *2/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-42	*02-21-96*	*1*	*SWS-5-1*			*20*	*2.8*						*20*		
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-43	*02-21-96*	*1*	*SWS-5-1*			*20*	*2.8*			*1.100*			*20*		
		2				*40*	*5.6*			*1.000*					
		3				*60*	*8.4*			*0.875*					
		4				*80*	*11.2*			*0.750*					
		5				*100*	*14.0*			*0.600*					
		6				*120*	*16.8*			*0.400*					
JE-44	*02-26-96*	*1*	*SWS-5-2*			*20*	*2.8*								
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								

TABLE B4-6 (continued)
Wet Chemistry Data
- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code *CFW9513* Page : *3/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-45	*02-26-96*	*1*	*SWS-5-2*			*20*	*2.8*			*1.125*					
		2				*40*	*5.6*			*1.000*					
		3				*60*	*8.4*			*0.875*					
		4				*80*	*11.2*			*0.750*					
		5				*100*	*14.0*			*0.600*					
		6				*120*	*16.8*			*0.450*					
JE-46	*02-27-96*	*1*	*SWS-5-2*			*20*	*2.8*						*40*		
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-47	*02-27-96*	*1*	*SWS-5-2*			*20*	*2.8*			*1.125*			*40*		
		2				*40*	*5.6*			*1.000*					
		3				*60*	*8.4*			*0.875*					
		4				*80*	*11.2*			*0.750*					
		5				*100*	*14.0*			*0.600*					
		6				*120*	*16.8*			*0.450*					

TABLE B4-6 (continued)
Wet Chemistry Data
- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process* Job Code *CFW9513* Page : *4/4*

Test Code	Test Date	Jar Code	Spiked Water Sample Code	Coagulant Dose						Acid Dose	Base Dose		Kaolin Dose	Ozone Feeding Rate	Remark
				Fe2(SO4)3		FeCl3		Alum		H2SO4	NaOH	Lime			
				mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Fe	mg/L as Liquid	mg/L as Al	mN/L	mN/L	mg/L as Solid	mg/L	mg/L	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
JE-49	*03-12-96*	*1*	*SWS-5-3*			*20*	*2.8*								
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								
JE-50	*03-13-96*	*1*	*SWS-5-4*			*20*	*2.8*								
		2				*40*	*5.6*								
		3				*60*	*8.4*								
		4				*80*	*11.2*								
		5				*100*	*14.0*								
		6				*120*	*16.8*								

TABLE B4-7
Treatability Data
- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process*   Job Code : *CFW9513*   Page : *1/4*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity			Particle Count								Arsenic				Remark
									Initial				Settled				Spiked with		Total	Dissolved	
						Initial	Settled	Filtered	2 µm	5 µm	10 µm	20 µm	2 µm	5 µm	10 µm	20 µm	III	V			
				mg/L as CaCO3	mg/L as CaCO3	NTU			Avg. Cuml. No./mL										ug/L		
1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-39	*1*	*SWS-5-1*	*7.50*	*98*		*0.23*	*0.22*		*328*	*59.3*	*14.1*	*0.86*	*1153*	*71.6*	*13.6*	*3.54*		*X*	*14.0*	*3.1*	Arsenic Analysis Data from : NDRC No. D96-1684
	2		*7.31*	*92*			*0.21*						*132*	*42.5*	*10.3*	*0.92*			*6.0*	*1.5*	
	3		*7.00*	*82*			*0.15*						*104*	*21.1*	*10.7*	*6.52*			*4.2*		
	4		*6.85*	*78*			*0.17*						*68.6*	*15.1*	*2.44*	*0.20*			*2.8*		
	5		*6.72*	*70*			*0.18*						*59.9*	*14.7*	*5.44*	*3.36*			*2.0*		
	6		*6.60*	*70*			*0.16*						*99.1*	*17.1*	*5.68*	*2.72*			*2.4*		
JE-40	*1*	*SWS-5-1*	*7.30*			*42.4*	*1.75*		*37425*	*8510*	*445*	*29.3*	*1234*	*200*	*42.0*	*3.20*		*X*	*12.8*	*3.2*	Arsenic Analysis Data from : NDRC No. D96-1684
	2		*7.16*				*1.06*						*313*	*84.9*	*20.4*	*1.00*			*6.1*	*1.8*	
	3		*7.00*				*0.42*						*175*	*59.3*	*15.1*	*1.08*			*3.2*	*1.7*	
	4		*6.87*				*0.29*						*129*	*48.1*	*13.2*	*1.16*			*2.4*	*1.2*	
	5		*6.72*				*0.26*						*85.0*	*34.6*	*12.9*	*1.32*			*1.0*		
	6		*6.65*				*0.21*						*99.4*	*31.2*	*9.28*	*0.76*			*1.0*		
JE-41	*1*	*SWS-5-1*	*7.44*			*10.7*	*0.78*						*1031*	*137*	*30.8*	*1.64*		*X*	*11.7*	*5.9*	Arsenic Analysis Data from : NDRC No. D96-1781
	2		*7.22*				*0.39*						*244*	*65.4*	*16.8*	*1.16*			*5.5*	*3.7*	
	3		*7.00*				*0.25*						*137*	*47.8*	*12.2*	*0.84*			*3.9*	*1.1*	
	4		*6.86*				*0.19*						*107*	*36.4*	*8.20*	*0.32*			*3.2*		
	5		*6.72*				*0.15*						*55.1*	*19.8*	*3.96*	*0.04*			*3.0*		
	6		*6.59*				*0.15*						*118*	*44.6*	*12.2*	*3.08*			*2.2*		

Note: When the measurement is lower than detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B4-7 (continued)

Treatability Data

- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process*

Job Code : *CFW9513*

Page : *2/4*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity			Particle Count								Arsenic				Remark
									Initial				Settled				Spiked with		Total	Dissolved	
						Initial	Settled	Filtered	2 um	5 um	10 um	20 um	2 um	5 um	10 um	20 um	III	V			
				mg/L as CaCO3	mg/L as CaCO3	NTU			Avg. Cumul. No./mL										mg/L		
1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-42	*1*	*SWS-5-1*	*7.36*			*21.3*	*1.19*						*1628*	*171*	*20.3*	*0.80*		*X*	*13.5*	*4.5*	Arsenic Analysis Data from : NDRC No. D96-1780 & 1782
	2		*7.15*				*0.60*						*367*	*101*	*35.1*	*2.28*			*7.3*	*3.7*	
	3		*6.96*				*0.31*						*137*	*36.3*	*11.0*	*0.80*			*4.1*	*1.9*	
	4		*6.85*				*0.20*						*124*	*28.2*	*6.36*	*0.16*			*3.8*		
	5		*6.67*				*0.17*						*68.0*	*30.5*	*11.56*	*0.92*			*2.0*		
	6		*6.47*				*0.15*						*167*	*39.2*	*10.14*	*0.52*			*1.4*		
JE-43	*1*	*SWS-5-1*	*6.25*	*42*		*21.5*	*13.70*						*26895*	*9298*	*1016*	*12.4*		*X*	*75.5*	*5.7*	Arsenic Analysis Data from : NDRC No. D96-1780 & 1782
	2		*6.18*	*40*			*1.67*						*1143*	*347*	*55.0*	*1.36*			*13.0*	*3.9*	
	3		*6.10*	*38*			*0.54*						*141*	*54.4*	*14.3*	*0.76*			*6.0*	*1.5*	
	4		*6.13*	*38*			*0.38*						*115*	*54.6*	*17.8*	*0.64*			*4.0*	*1.2*	
	5		*6.11*	*38*			*0.36*						*360*	*160*	*42.3*	*0.64*			*2.2*	*1.7*	
	6		*6.31*	*40*			*0.37*						*376*	*164*	*44.6*	*1.64*			*2.1*	*1.0*	
JE-44	*1*	*SWS-5-2*	*7.25*			*0.23*	*0.24*						*109*	*21.9*	*4.24*	*0.08*		*X*	*7.2*	*3.1*	Arsenic Analysis Data from : NDRC No. D96-1960
	2		*7.14*				*0.25*						*45.1*	*6.00*	*0.92*	*0.04*			*3.9*	*1.8*	
	3		*7.00*				*0.18*						*46.4*	*11.7*	*2.64*	*0.20*			*2.2*	*2.2*	
	4		*6.85*				*0.16*						*76.0*	*11.5*	*2.48*	*0.12*			*2.4*	*1.2*	
	5		*6.74*				*0.16*						*56.4*	*13.5*	*3.48*	*0.40*			*1.3*		
	6		*6.62*				*0.15*						*117*	*20.6*	*3.60*	*0.12*			*1.5*		

Note: When the measurement is lower than detection limit, the detection limit for that analysis is used as the result (underlined value).

TABLE B4-7 (continued)
Treatability Data
- Arsenic REmoval Mechanism Experiment -

Project : Arsenic Removal in Water Treatment Process

Job Code : CFW9513

Page : 3/4

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity			Particle Count								Arsenic				Remark
									Initial				Settled				Spiked with		Total	Dissolved	
						Initial	Settled	Filtered	2 um	5 um	10 um	20 um	2 um	5 um	10 um	20 um					
				mg/L as CaCO3	mg/L as CaCO3	NTU			Avg. Cuml. No./mL								III	V	mg/L		
1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-45	1	SWS-5-2	6.25			0.23							213	32.3	7.16	0.16		X			Arsenic Analysis Data from : NDRC No. D96-1968
	2		6.24				0.74						132	13.4	3.56	0.16			7.0	2.1	
	3		6.15				0.54						78.0	13.0	1.96	0.12			3.9	2.0	
	4		6.14				0.50						80.2	8.32	1.84	0.12			2.1	1.6	
	5		6.14				0.31						107	13.2	1.88	0.08			2.0	1.5	
	6		6.13				0.27						105	18.9	4.24	0.44			1.0	1.4	
JE-46	1	SWS-5-2	7.22			44.6	1.83		38905	10461	969	65.2	2344	224	22.7	1.52		X	5.3	2.3	Arsenic Analysis Data from : NDRC No. D96-2221
	2		7.17				1.10						581	82.5	24.8	3.16			3.1	2.0	
	3		7.01				0.52						136	41.3	10.5	1.08			2.3	1.0	
	4		6.85				0.27						131	46.1	14.3	1.64			1.4	1.6	
	5		6.71				0.25						236	110	51.6	16.7			1.0		
	6		6.60				0.22						116	48.4	22.2	3.40			1.0		
JE-47	1	SWS-5-2	6.15			44.6	28.10						38429	12661	803	3.32		X	37.8	8.7	Arsenic Analysis Data from : NDRC No. D96-2221
	2		6.10				1.44						1163	347	63.0	1.44			6.6	1.0	
	3		6.08				0.53						221	87.1	24.4	1.68			2.3	2.0	
	4		6.07				0.41						133	56.4	20.8	2.12			1.1	1.0	
	5		6.08				0.35						243	117	41.4	2.16			1.0	1.0	
	6		6.08				0.30						212	102	38.4	2.08			1.0	1.0	

Note: When the measurement is lower than detection limit, the detection limit for that analysis is used as the result (underlined value).

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TABLE B4-7 (continued)
Treatability Data
- Arsenic REmoval Mechanism Experiment -

Project : *Arsenic Removal in Water Treatment Process*
Job Code : *CFW9513*
Page : *4/4*

Test Code	Jar Code	Spiked Water Sample Code	Final pH	Total Alkalinity	Total Hardness	Turbidity			Particle Count								Arsenic				Remark
									Initial				Settled				Spiked with		Total	Dissolved	
						Initial	Settled	Filtered	2 µm	5 µm	10 µm	20 µm	2 µm	5 µm	10 µm	20 µm	III	V			
				mg/L as CaCO3	mg/L as CaCO3	NTU			Avg. Cuml. No./mL										µg/L		
1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16	17	18	19	20	21
JE-49	*1*	*SWS-5-3*	*7.52*	*103*		*0.23*	*0.26*											*X*	*3.3*		Arsenic Analysis Data from : NDRC No. D96-2612
	2		*7.16*	*95*			*0.18*												*1.9*	*1.7*	
	3		*7.00*	*90*			*0.20*												*1.5*	*1.1*	
	4		*6.87*	*81*			*0.20*												*1.7*	*1.0*	
	5		*6.70*	*74*			*0.18*												*1.6*		
	6		*6.63*	*68*			*0.13*												*1.3*		
JE-50	*1*	*SWS-5-4*	*7.41*			*0.25*												*X*	*1.5*	*1.0*	Arsenic Analysis Data from : NDRC No. D96-2667
	2		*7.06*																*1.0*	*1.0*	
	3		*6.91*																*1.0*	*1.0*	
	4		*6.82*																*1.0*	*1.8*	
	5		*6.67*																*1.0*		
	6		*6.57*																*1.0*		

Note: When the measurement is lower than detection limit, the detection limit for that analysis is used as the result (underlined value).

APPENDIX C

INFORMATION ABOUT pH ADJUSTMENT

FIGURES

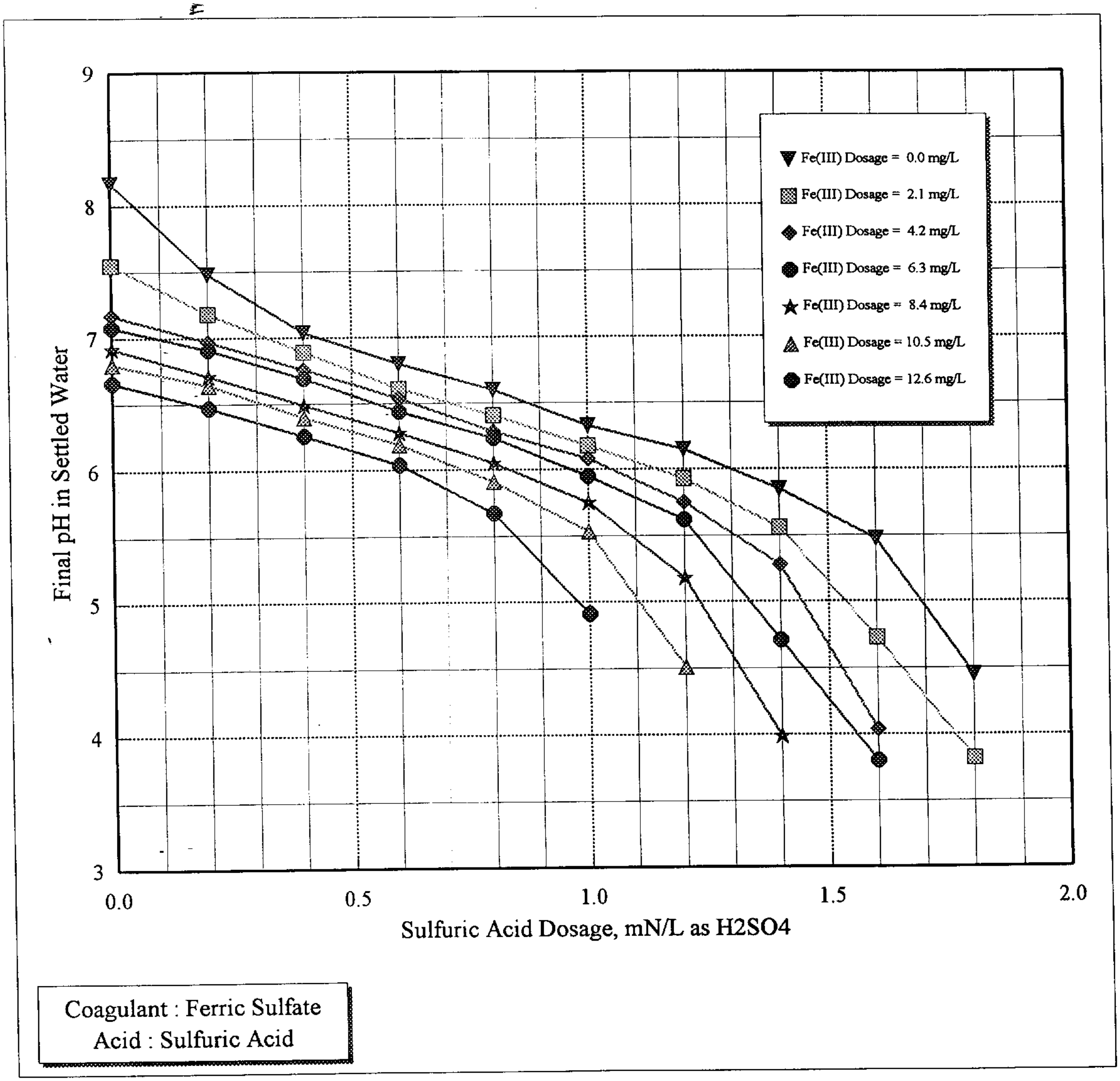

FIGURE C-1

pH Adjustment Curves for Ferric Sulfate with Sulfuric Acid

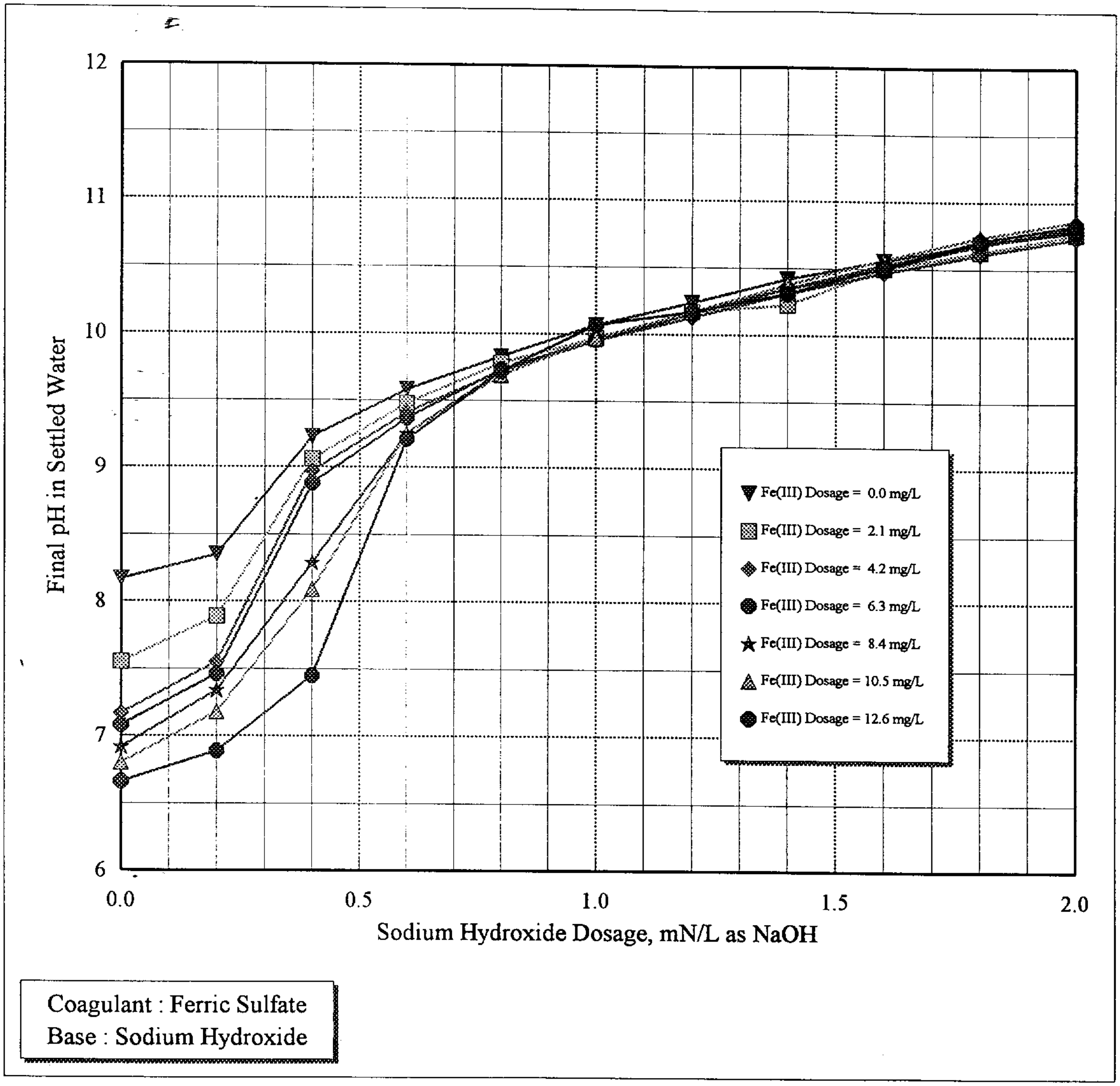

FIGURE C-2

pH Adjustment Curves for Ferric Sulfate with Sodium Hydroxide

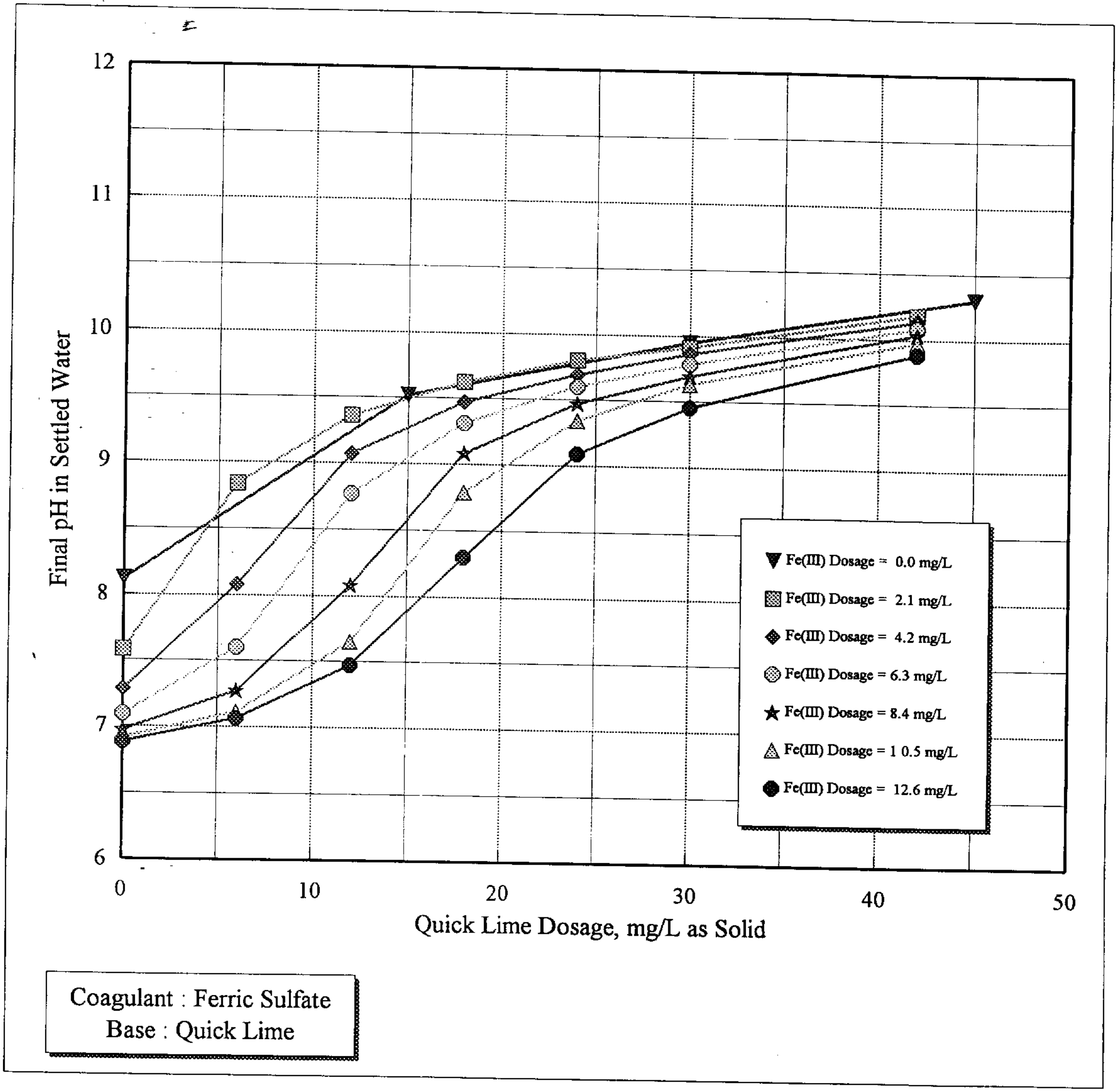

FIGURE C-3

pH Adjustment Curves for Ferric Sulfate with Quick Lime

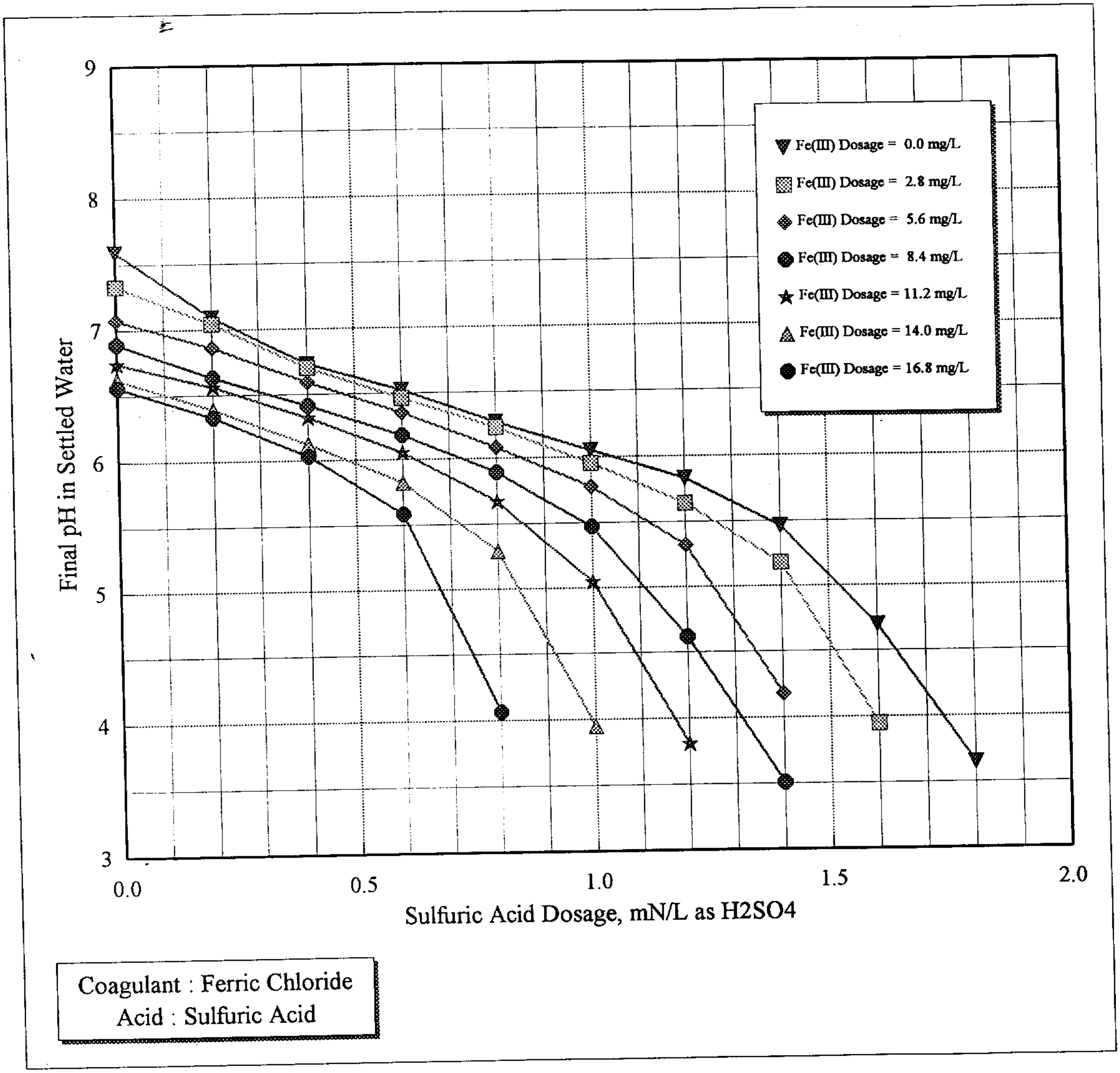

FIGURE C-4

pH Adjustment Curves for Ferric Chloride with Sulfuric Acid

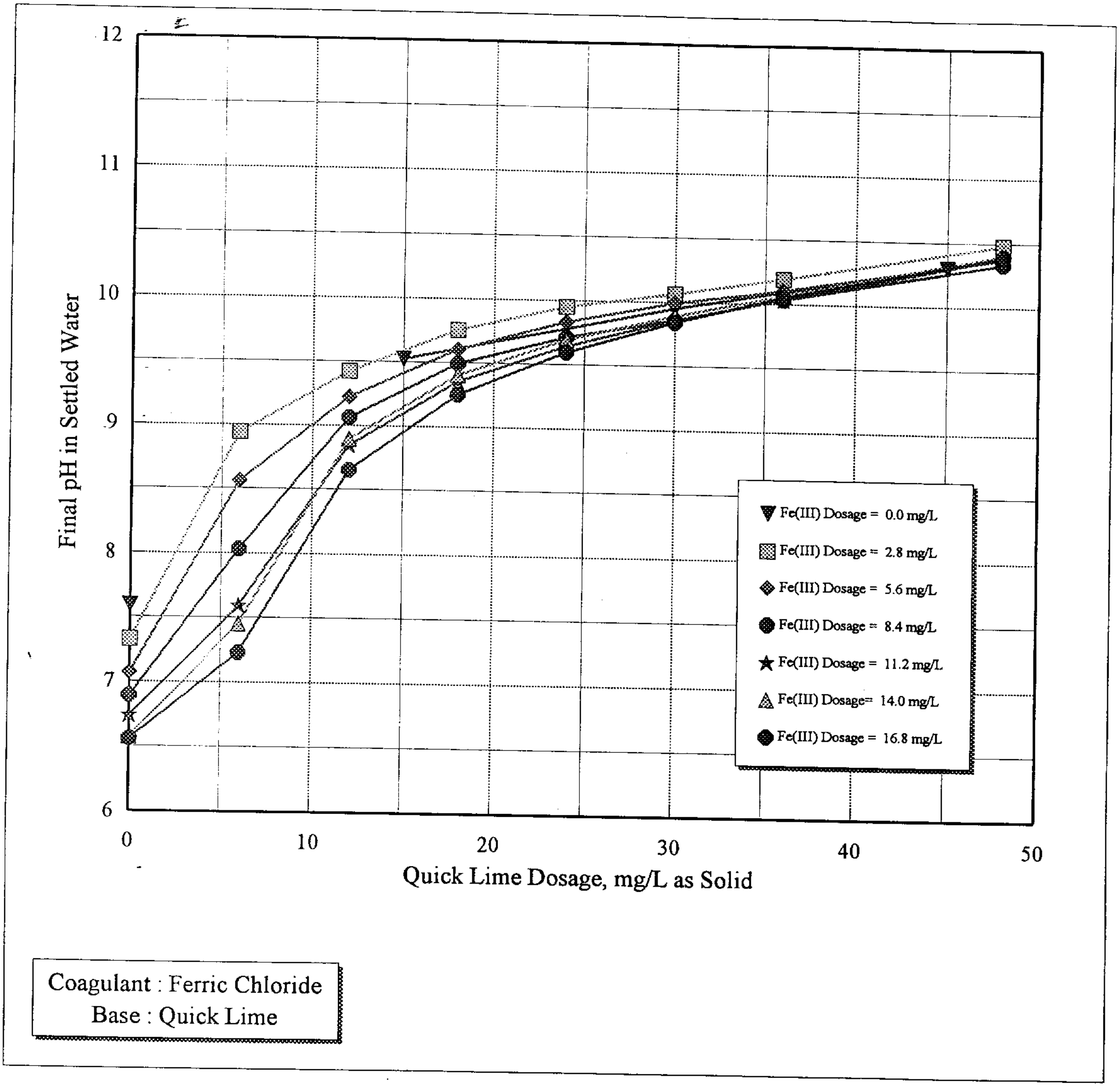

FIGURE C-5

pH Adjustment Curves for Ferric Chloride with Quick Lime

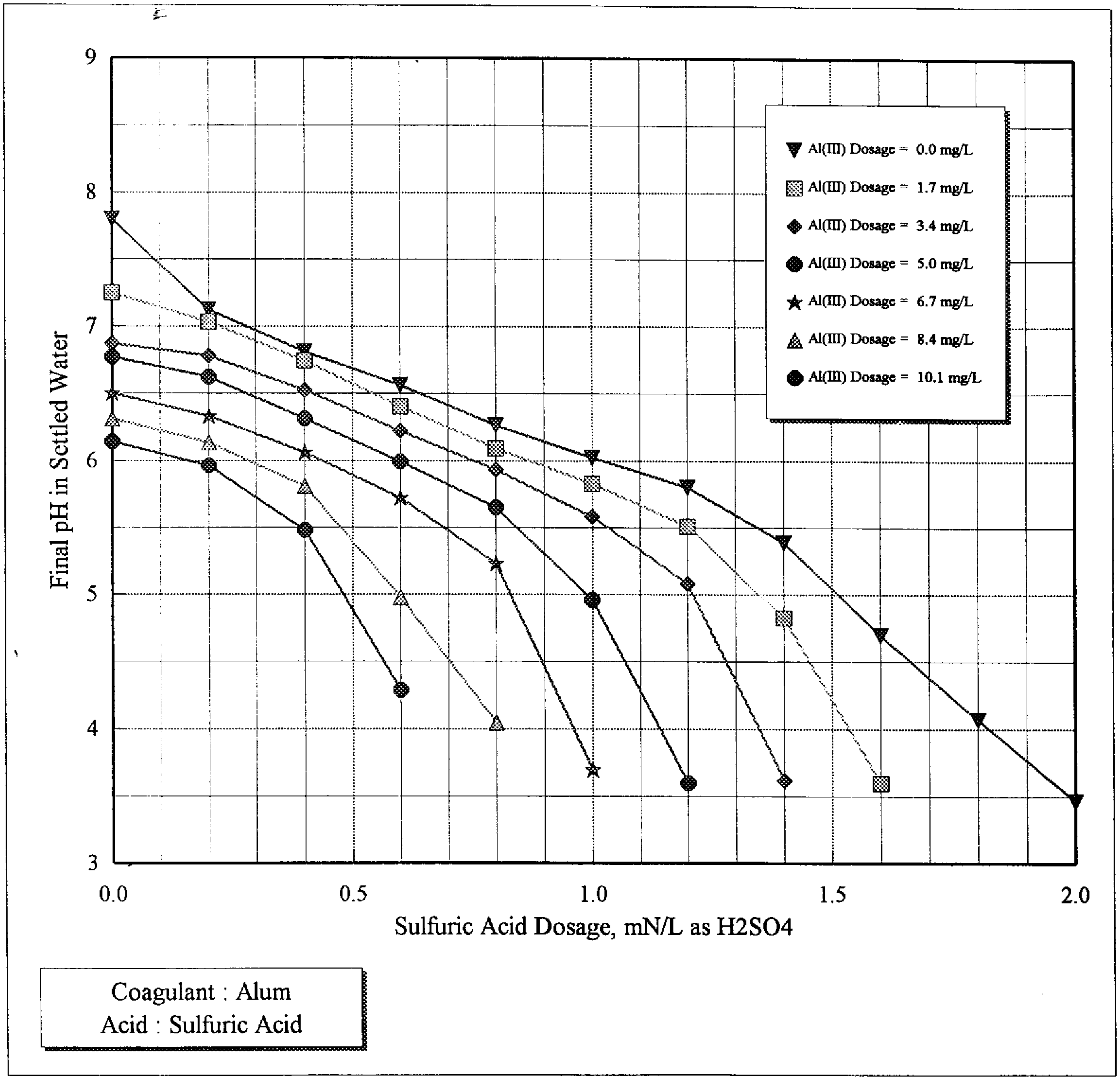

FIGURE C-6

pH Adjustment Curves for Alum with Sulfuric Acid

APPENDIX D

INFORMATION ABOUT KAOLIN SPIKING

FIGURE

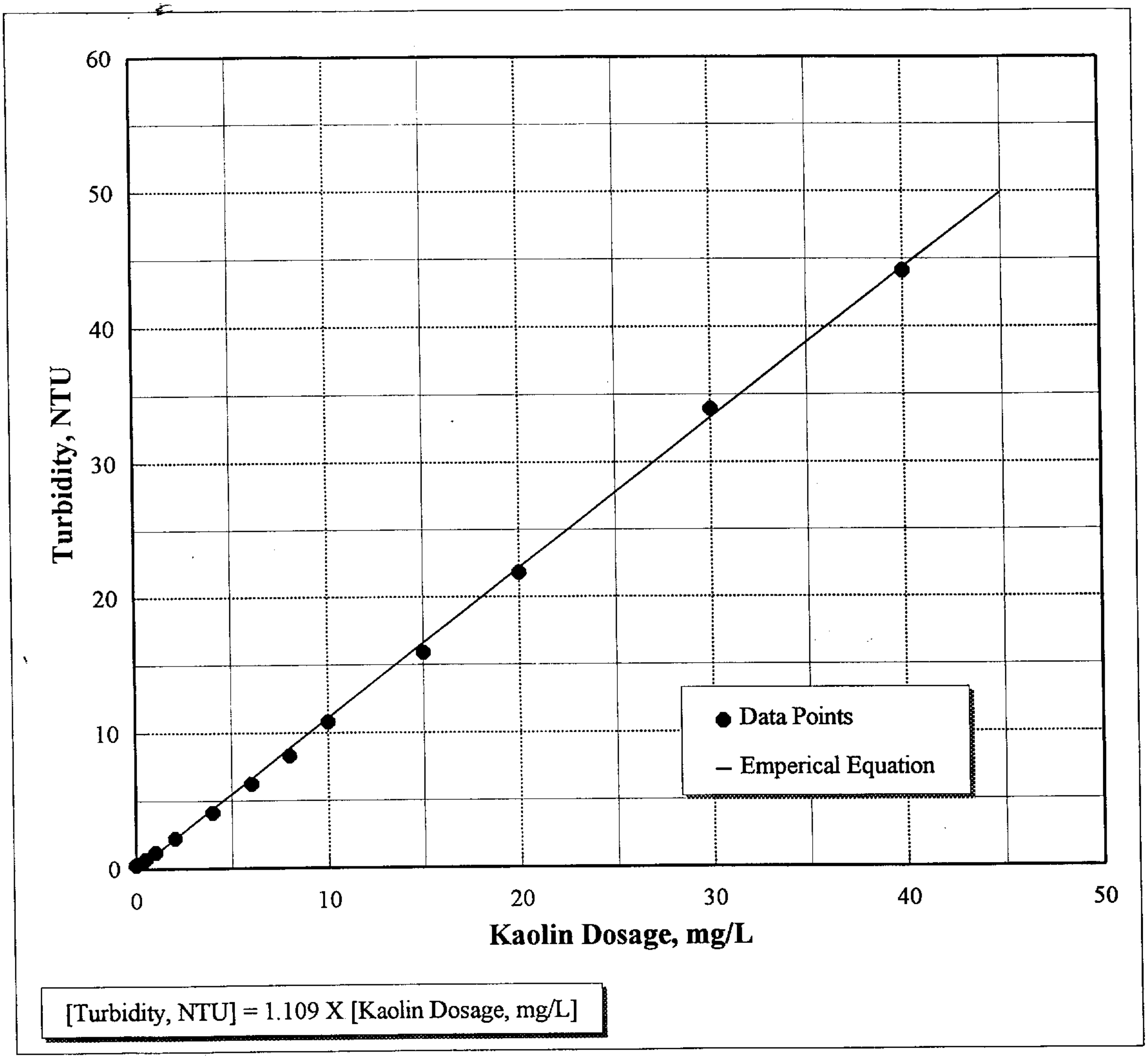

FIGURE D-1

Relationship between Turbidity and Kaolin Dosage

APPENDIX E

COAGULATION DIAGRAMS

(DATA POINTS)

FIGURES

FIGURES (continued)

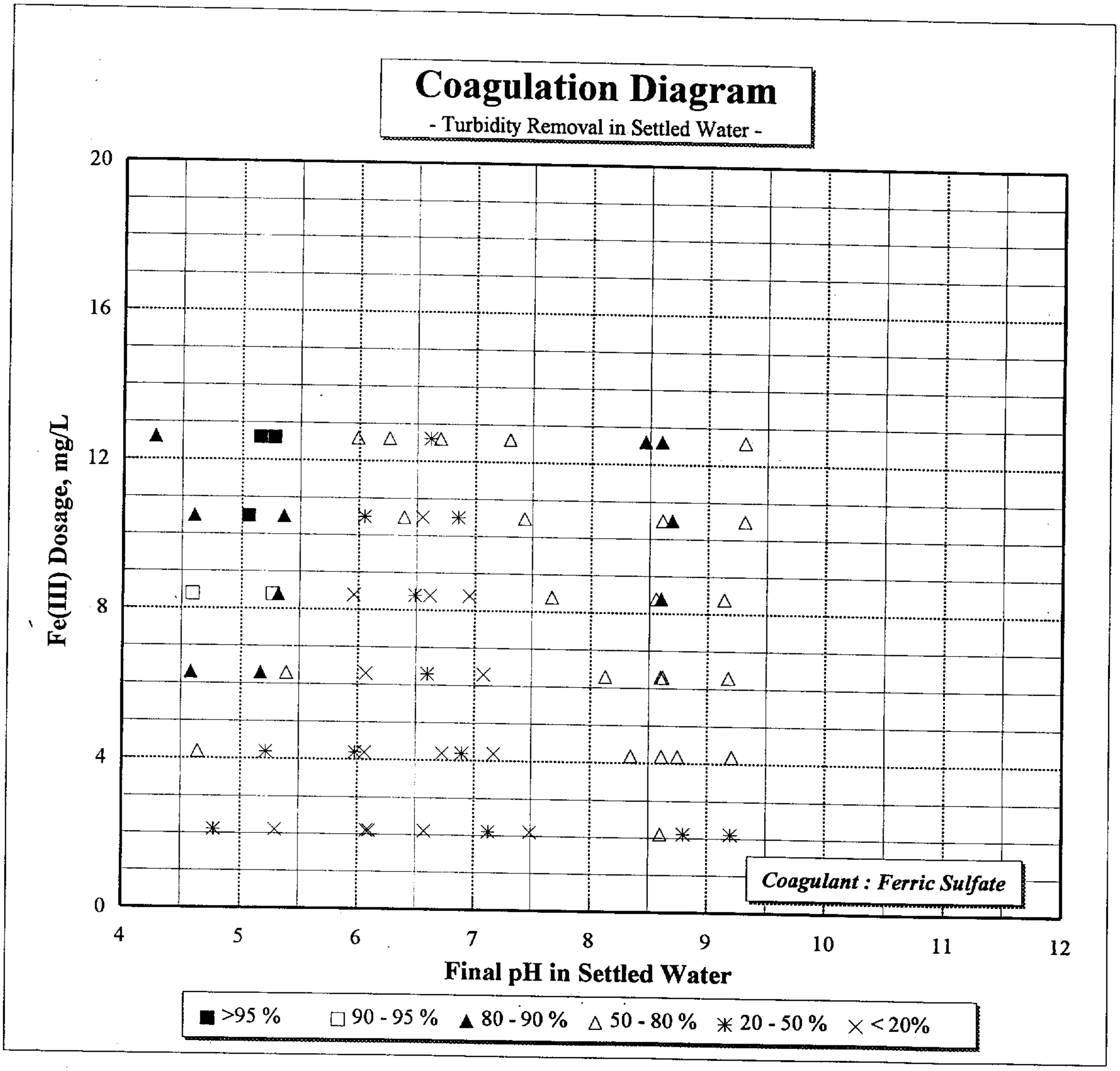

FIGURE E-1

Coagulation Diagram (Data Points) for Turbidity Removal

in Settled Water with Ferric Sulfate Coagulation

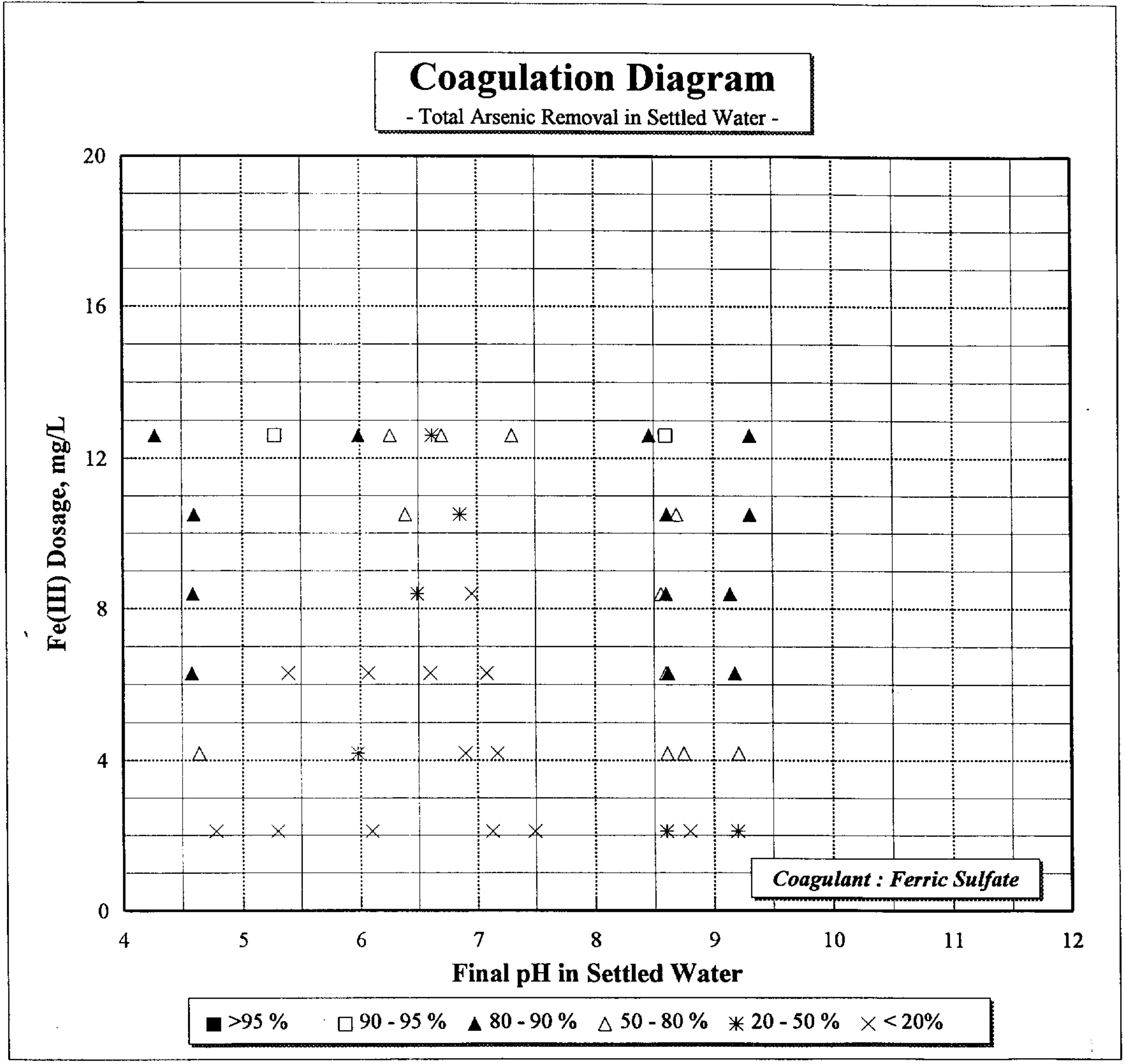

FIGURE E-2

Coagulation Diagram (Data Points) for Total Arsenic Removal

in Settled Water with Ferric Sulfate Coagulation

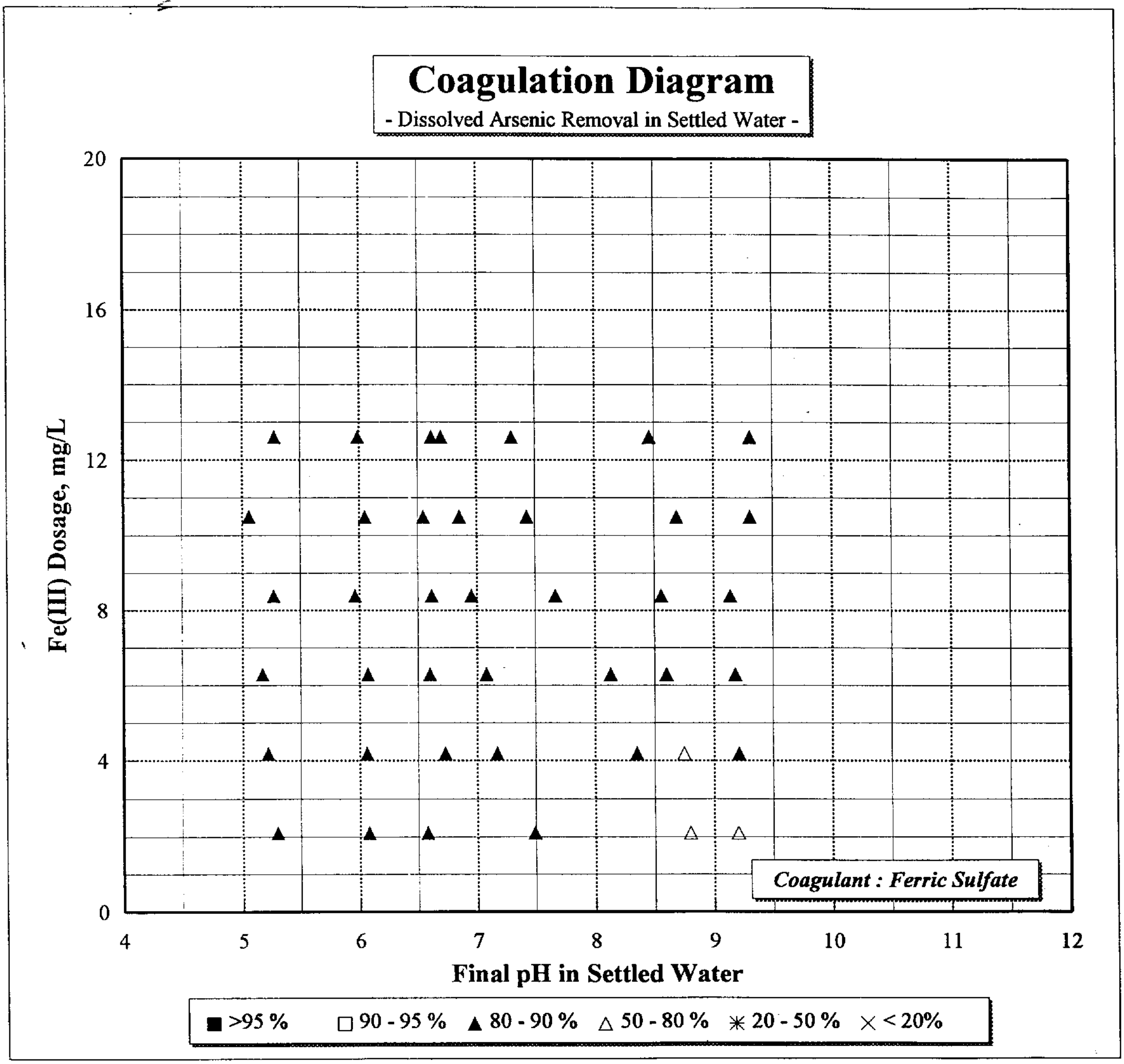

FIGURE E-3

Coagulation Diagram (Data Points) for Dissolved Arsenic Removal

in Settled Water with Ferric Sulfate Coagulation

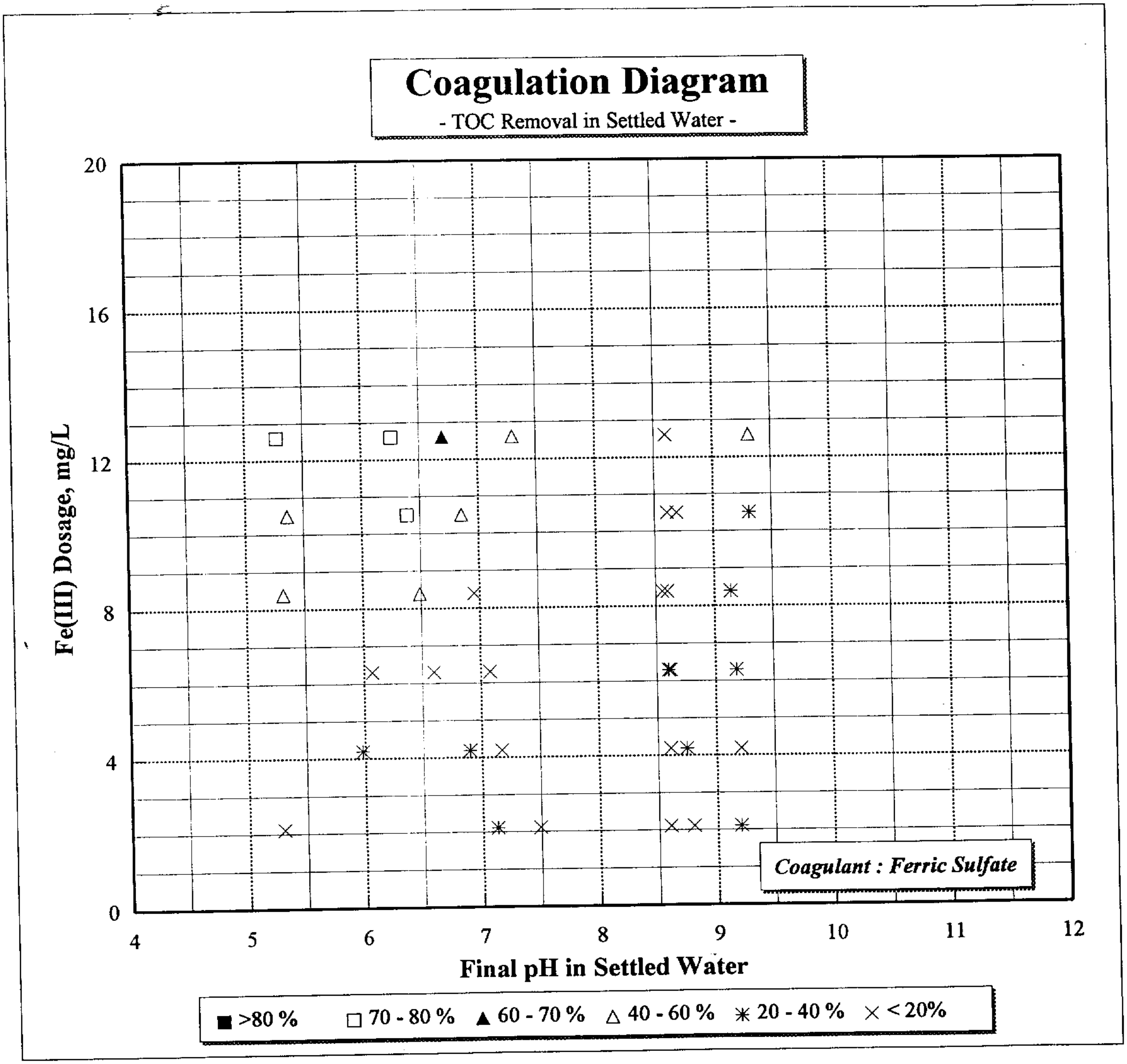

FIGURE E-4

Coagulation Diagram (Data Points) for Total Organic Carbon Removal

in Settled Water with Ferric Sulfate Coagulation

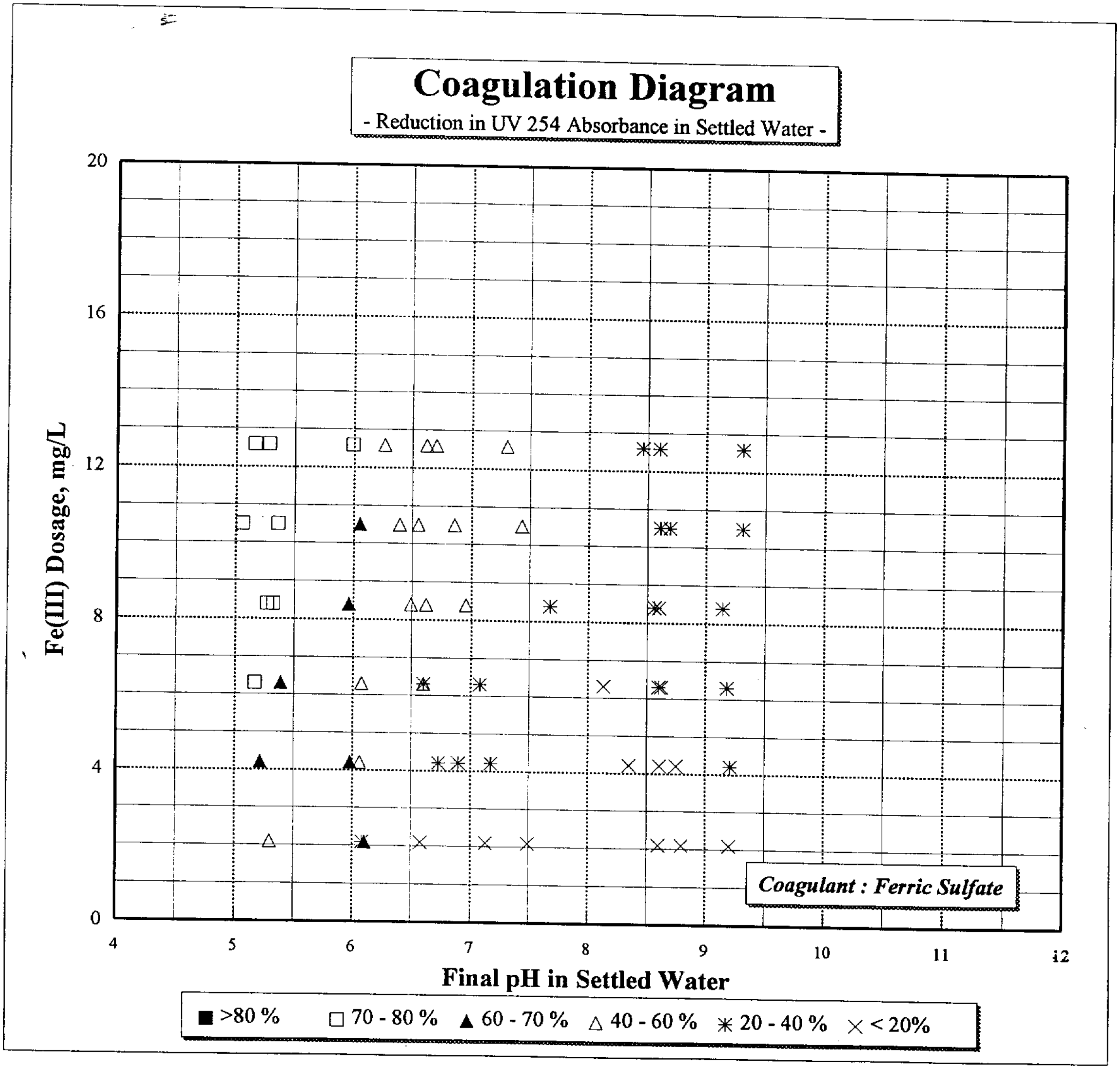

FIGURE E-5

Coagulation Diagram (Data Points) for Reduction in UV254 Absorbance

in Settled Water with Ferric Sulfate Coagulation

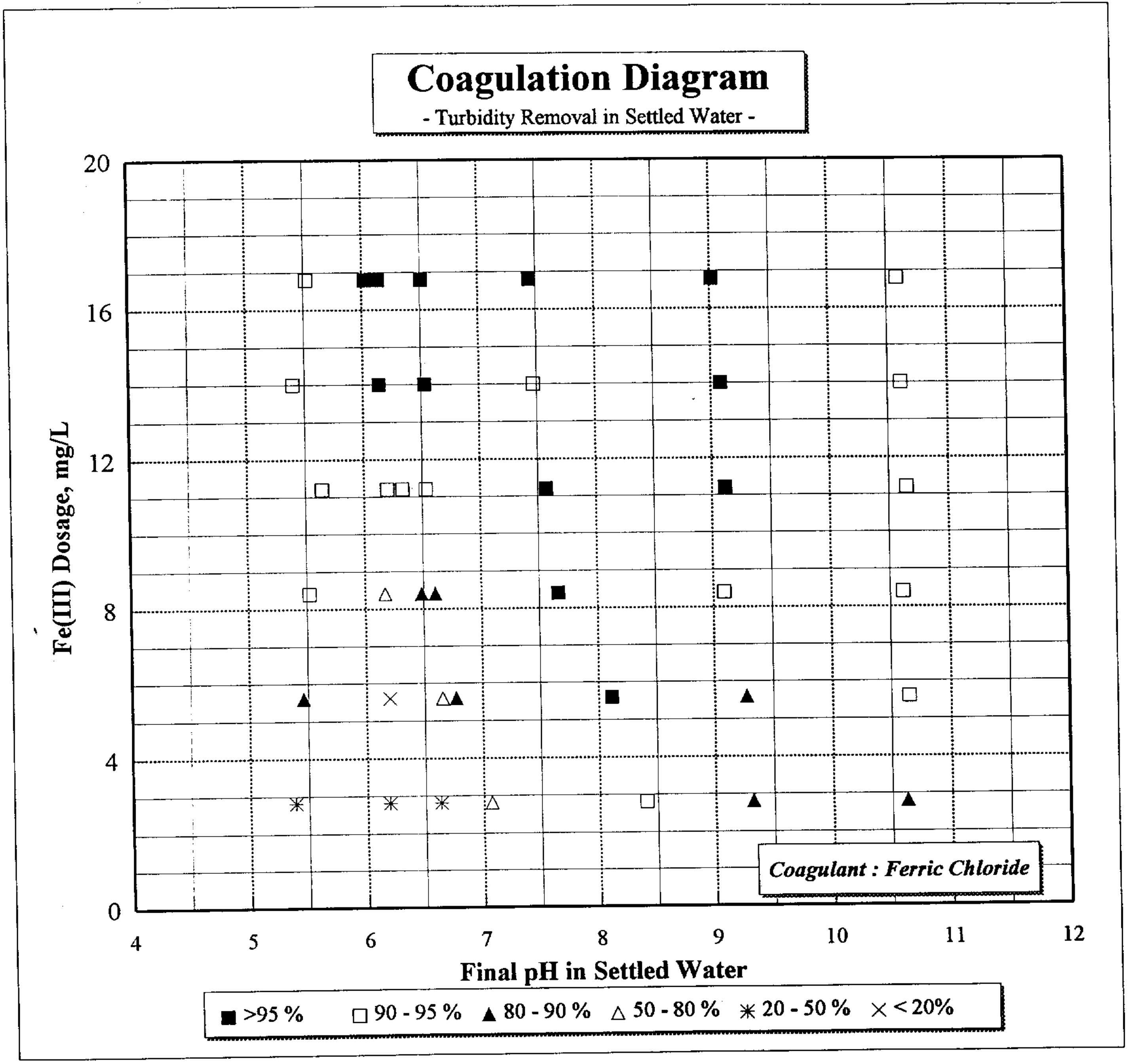

FIGURE E-6

Coagulation Diagram (Data Points) for Turbidity Removal

in Settled Water with Ferric Chloride Coagulation

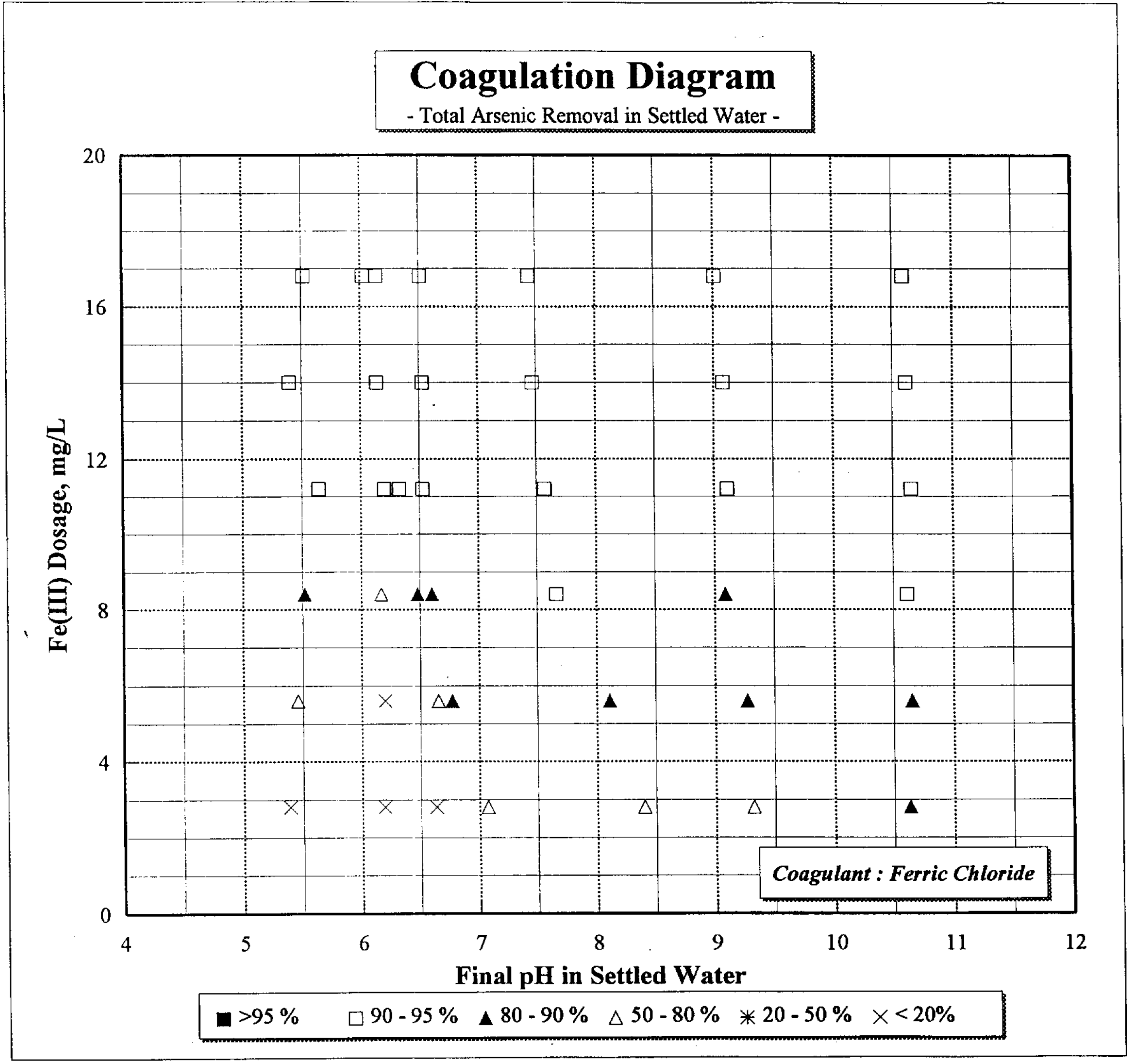

FIGURE E-7

Coagulation Diagram (Data Points) for Total Arsenic Removal

in Settled Water with Ferric Chloride Coagulation

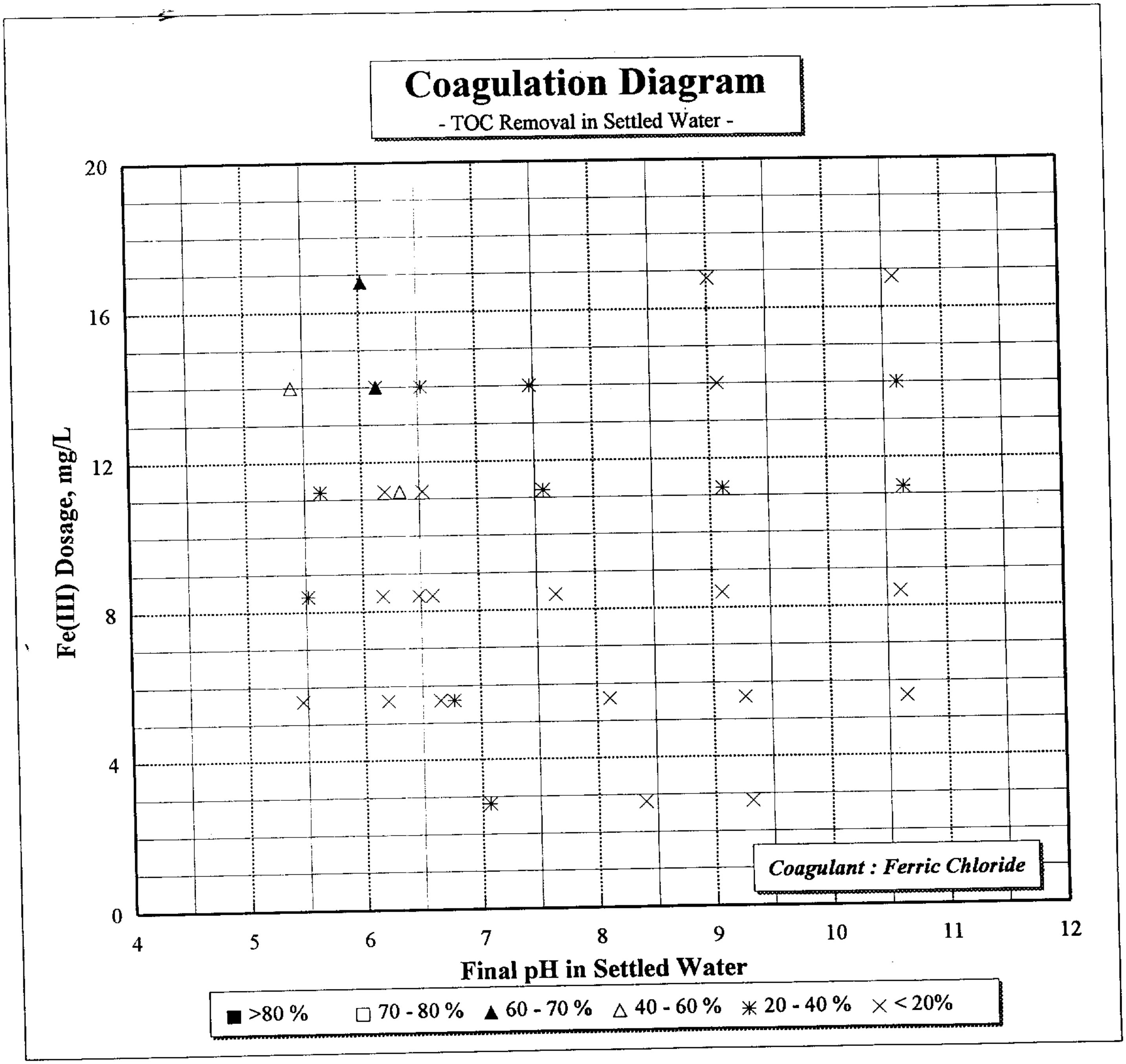

FIGURE E-8

Coagulation Diagram (Data Points) for Total Organic Carbon Removal

in Settled Water with Ferric Chloride Coagulation

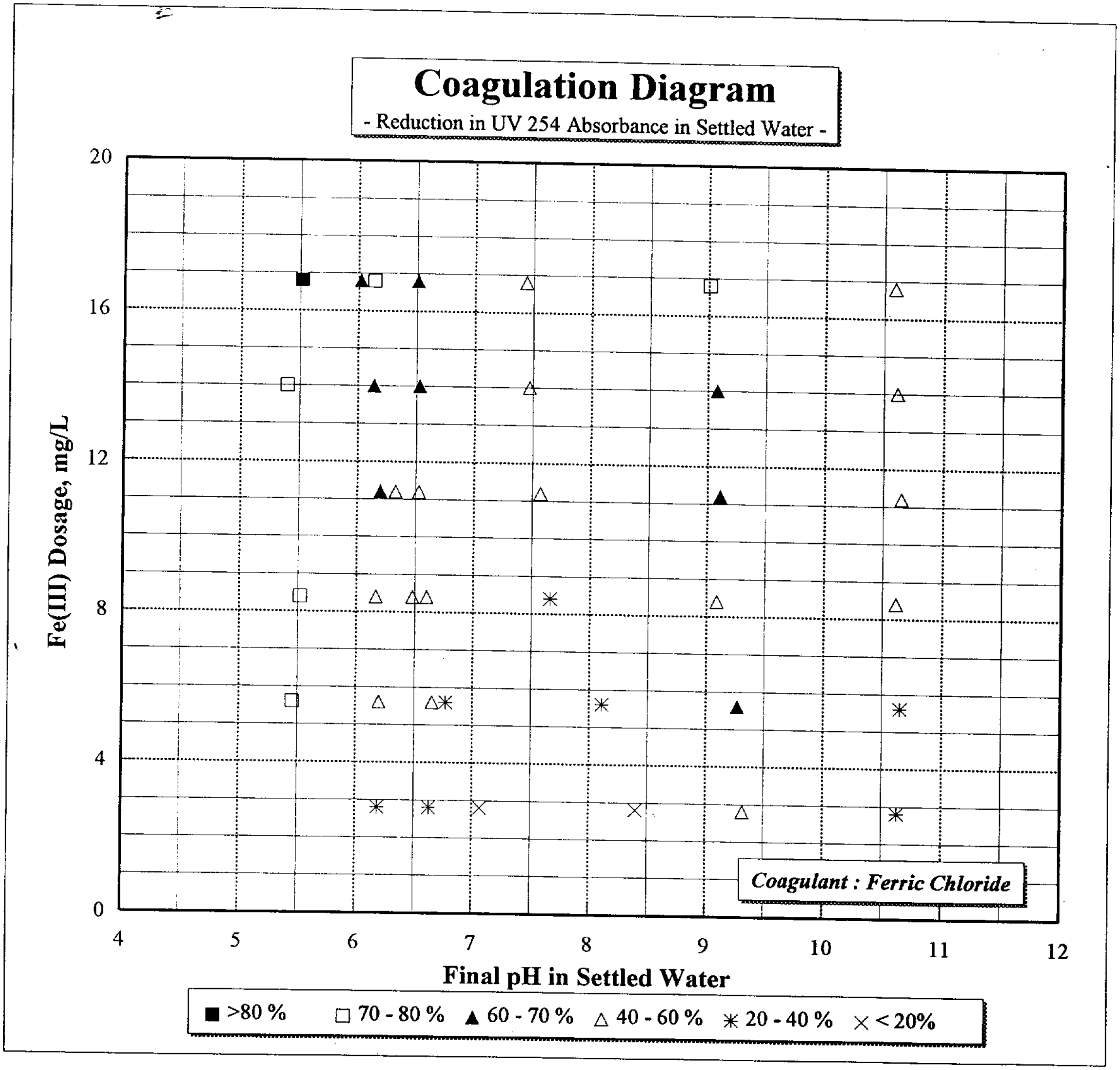

FIGURE E-9

Coagulation Diagram (Data Points) for Reduction in UV254 Absorbance

in Settled Water with Ferric Chloride Coagulation

APPENDIX F

ARSENIC REMOVAL AND ITS CONCENTRATION IN SLUDGE

TABLE

TABLE F-1

Arsenic Removal and Its Concentration in Sludge

Fe(III) Dosage mg/L	Sludge Mass mg/L (Eq. (4-2))	Initial Total Arsenic Concentration, ug/L														
		5	10	20	30	50	5	10	20	30	50	5	10	20	30	50
		Arsenic in Finished Water, ug/L (Eq. (4-8))					Arsenic Removal, ug/L (Eq. (4-9))					Arsenic in Sludge, g/kg (Eq. (4-4))				
0.0	10.00	5.00	10.00	20.00	30.00	50.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2	10.34	2.31	4.20	7.98	11.77	19.34	2.69	5.80	12.02	18.23	30.66	0.26	0.56	1.16	1.76	2.97
0.4	10.68	1.68	2.84	5.18	7.51	12.18	3.32	7.16	14.82	22.49	37.82	0.31	0.67	1.39	2.11	3.54
0.6	11.01	1.40	2.24	3.93	5.61	8.99	3.60	7.76	16.07	24.39	41.01	0.33	0.70	1.46	2.21	3.72
0.8	11.35	1.24	1.90	3.22	4.54	7.18	3.76	8.10	16.78	25.46	42.82	0.33	0.71	1.48	2.24	3.77
1.0	11.69	1.13	1.68	2.76	3.85	6.02	3.87	8.32	17.24	26.15	43.98	0.33	0.71	1.47	2.24	3.76
1.5	12.54	0.99	1.37	2.12	2.87	4.37	4.01	8.63	17.88	27.13	45.63	0.32	0.69	1.43	2.16	3.64
2.0	13.38	0.91	1.20	1.77	2.35	3.50	4.09	8.80	18.23	27.65	46.50	0.31	0.66	1.36	2.07	3.48
2.5	14.23	0.87	1.10	1.56	2.03	2.96	4.13	8.90	18.44	27.97	47.04	0.29	0.63	1.30	1.97	3.31
3.0	15.07	0.83	1.03	1.42	1.81	2.59	4.17	8.97	18.58	28.19	47.41	0.28	0.60	1.23	1.87	3.15
3.5	15.92	0.81	0.98	1.31	1.65	2.32	4.19	9.02	18.69	28.35	47.68	0.26	0.57	1.17	1.78	3.00
4.0	16.76	0.79	0.94	1.24	1.53	2.12	4.21	9.06	18.76	28.47	47.88	0.25	0.54	1.12	1.70	2.86
4.5	17.61	0.78	0.91	1.17	1.44	1.96	4.22	9.09	18.83	28.56	48.04	0.24	0.52	1.07	1.62	2.73
5.0	18.45	0.77	0.89	1.12	1.36	1.84	4.23	9.11	18.88	28.64	48.16	0.23	0.49	1.02	1.55	2.61
5.5	19.30	0.76	0.87	1.08	1.30	1.73	4.24	9.13	18.92	28.70	48.27	0.22	0.47	0.98	1.49	2.50
6.0	20.14	0.75	0.85	1.05	1.25	1.65	4.25	9.15	18.95	28.75	48.35	0.21	0.45	0.94	1.43	2.40
6.5	20.99	0.74	0.84	1.02	1.20	1.57	4.26	9.16	18.98	28.80	48.43	0.20	0.44	0.90	1.37	2.31
7.0	21.83	0.74	0.82	0.99	1.17	1.51	4.26	9.18	19.01	28.83	48.49	0.20	0.42	0.87	1.32	2.22
7.5	22.68	0.73	0.81	0.97	1.13	1.45	4.27	9.19	19.03	28.87	48.55	0.19	0.41	0.84	1.27	2.14
8.0	23.52	0.73	0.80	0.95	1.10	1.40	4.27	9.20	19.05	28.90	48.60	0.18	0.39	0.81	1.23	2.07
8.5	24.37	0.73	0.80	0.94	1.08	1.36	4.27	9.20	19.06	28.92	48.64	0.18	0.38	0.78	1.19	2.00
9.0	25.21	0.72	0.79	0.92	1.06	1.32	4.28	9.21	19.08	28.94	48.68	0.17	0.37	0.76	1.15	1.93
9.5	26.06	0.72	0.78	0.91	1.04	1.29	4.28	9.22	19.09	28.96	48.71	0.16	0.35	0.73	1.11	1.87
10.0	26.90	0.72	0.78	0.90	1.02	1.26	4.28	9.22	19.10	28.98	48.74	0.16	0.34	0.71	1.08	1.81
11.0	28.59	0.71	0.77	0.88	0.99	1.20	4.29	9.23	19.12	29.01	48.80	0.15	0.32	0.67	1.01	1.71
12.0	30.28	0.71	0.76	0.86	0.96	1.16	4.29	9.24	19.14	29.04	48.84	0.14	0.31	0.63	0.96	1.61
13.0	31.97	0.70	0.75	0.84	0.94	1.12	4.30	9.25	19.16	29.06	48.88	0.13	0.29	0.60	0.91	1.53
14.0	33.66	0.70	0.74	0.83	0.92	1.09	4.30	9.26	19.17	29.08	48.91	0.13	0.27	0.57	0.86	1.45
15.0	35.35	0.70	0.74	0.82	0.90	1.06	4.30	9.26	19.18	29.10	48.94	0.12	0.26	0.54	0.82	1.38
16.0	37.04	0.70	0.73	0.81	0.89	1.04	4.30	9.27	19.19	29.11	48.96	0.12	0.25	0.52	0.79	1.32
17.0	38.73	0.69	0.73	0.80	0.87	1.01	4.31	9.27	19.20	29.13	48.99	0.11	0.24	0.50	0.75	1.26
18.0	40.42	0.69	0.73	0.79	0.86	1.00	4.31	9.27	19.21	29.14	49.00	0.11	0.23	0.48	0.72	1.21
19.0	42.11	0.69	0.72	0.79	0.85	0.98	4.31	9.28	19.21	29.15	49.02	0.10	0.22	0.46	0.69	1.16
20.0	43.80	0.69	0.72	0.78	0.84	0.96	4.31	9.28	19.22	29.16	49.04	0.10	0.21	0.44	0.67	1.12

Note : assume initial total suspended solids in raw water is 10 mg/L

APPENDIX G

PILOT PLANT INFORMATION

TABLE

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	2	3	4	5.0	6	12
10/04/95	Raw	800	7.30	---------	2.80	36.1	18.1			Ferric Sulfate Dosage (mg/l as liquid) = 30 Species = As (III) Notes : Used filter #1 No pH adjustment
	Filtered	800	7.60	88	1.00	34.1	17.1			
	Raw	1300	7.60	88	3.77	39.2	19.6			
1	Settled	1300	7.31	82	2.21	24.3	12.2			
	Filtered	1300	7.33	82	0.40	17.4	8.7			
	Raw	1600	7.38	92	2.83	39.4	19.7			
2	Settled	1600	7.34	82	2.20	25.4	12.7			
	Filtered	1600	7.29	82	0.33	17.7	8.9			
10/05/95	Raw	2400	7.70	91	2.67	40.4	20.2			
01/03/00	Settled	2400	7.58	83	2.26	27.9	14.0			
	Filtered	2400	7.57	82	0.67	29.3	14.7			
10/12/95	Raw	805	7.46	78	2.86	33.9	17.0			Ferric Sulfate Dosage (mg/l as liquid) = 60 Species = As (III) Notes : Switched from filter #1 to filter #3 at 1000 hours No pH adjustment
4	Settled	805	7.00	58	2.12	15.0	7.5			
	Filtered	805	7.05	60	0.46	9.4	4.7			
	Raw	1200	7.38	77	14.7*	34.7	17.4			
5	Settled	1200	6.94	60	3.02	17.0	8.5			
	Filtered	1200	7.21	68	0.34	5.6	2.8			
	Raw	1500	7.34	80	2.97	36.3	18.2			
6	Settled	1500	6.91	60	2.67					
	Filtered	1500	7.16	67	0.36	8.3	4.2			
10/13/95	Raw	900	7.24	90	5.66	36.6	18.3			Ferric Sulfate Dosage (mg/l as liquid) = 90 Species = As (III) Notes : Used filter #1 No pH adjustment
7	Settled	900	6.81	61	2.48	7.7	3.9			
	Filtered	900	6.87	63	0.49	6.9	3.5			
	Raw	1200	7.36	88	6.26	30.3	15.2			
8	Settled	1200	6.86	62	2.81	7.2	3.6			
	Filtered	1200	6.84	60	0.16	8.1	4.1			
	Raw	1500	7.35	87	7.51					
9	Settled	1500	6.85	62	3.46					
	Filtered	1500	6.86	62	0.17					

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
10/19/95	Raw	820	7.66	90	5.39	16.8				
10	Settled	820	7.04	72	2.58	6.2				Ferric Sulfate Dosage (mg/l as liquid) = 60
	Filtered	820	7.03	71	0.23	1.0				
	Raw	1200	7.57	90	4.70	19.6				Species = As (V)
11	Settled	1200	7.01	74	2.93	8.3				Notes :
	Filtered	1200	7.00	74	0.54	2.5				Used filter #1
	Raw	1500	7.62	90	3.46	18.3				No pH adjustment
12	Settled	1500	7.09	75	3.00	10.4				
	Filtered	1500	7.03	73	0.56	1.0				
10/20/95	Raw	845	7.58	88	5.13	17.4				
13	Settled	845	6.82	64	2.33	5.4				Ferric Sulfate Dosage (mg/l as liquid) = 90
	Filtered	845	6.96	70	0.15	1.0				
	Raw	1200	7.61	88	3.95	19.6				Species = As (V)
14	Settled	1200	6.81	63	2.29	4.9				Notes :
	Filtered	1200	7.00	72	0.13	2.2				Used filter #3
	Raw	1500	7.31	86	4.13	23.0				No pH adjustment
15	Settled	1500	6.77	62	2.36	6.9				
	Filtered	1500	6.98	70	0.11	1.0				
10/24/95	Raw	815	7.57	88	4.45	18.5				
16	Settled	815	7.43	81	3.03	11.0				Ferric Sulfate Dosage (mg/l as liquid) = 30
	Filtered	815	7.44	82	0.55	1.3				
	Raw	1200	7.71	88	6.36	15.0				Species = As (V)
17	Settled	1200	7.34	81	3.65	10.8				Notes :
	Filtered	1200	7.34	81	0.52	1.5				Used filter #1
	Raw	1500	7.73	90	4.33	16.0				No pH adjustment
18	Settled	1500	7.38	82	3.80	14.2				
	Filtered	1500	7.36	82	0.70	1.5				

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
10/25/95	Raw	835	7.77	89	4.56	18.0				Ferric Sulfate Dosage (mg/l as liquid) = 60
19	Settled	835	8.41	91	2.17	6.4				NaOH Dosage (mg/l) = 16
	Filtered	835	8.46	92	0.17	1.7				
	Raw	1200	7.76	90	5.03	16.9				Species = As (V)
20	Settled	1200	7.81	91	2.61	8.2				Notes :
	Filtered	1200	7.93	92	0.17	1.5				Used filter #3
	Raw	1500	7.77	92	4.50	19.7				pH target 8.5 - first samples close, but later samples dropped off
21	Settled	1500	7.93	91	2.57	6.6				
	Filtered	1500	8.00	92	0.14	1.0				
10/26/95	Raw	840	7.77	99	4.88	22.0				Ferric Sulfate Dosage (mg/l as liquid) = 60
22	Settled	840	9.67	97	2.27	5.9				NaOH Dosage (mg/l) = 38
	Filtered	840	9.54	83	0.15	4.2				
	Raw	1200	7.80	88	5.38	19.0				Species = As (V)
23	Settled	1200	9.64	99	2.73	6.2				Notes :
	Filtered	1200	9.39	82	0.20	3.9				Used filter #1
	Raw	1500	7.80	88	4.81	23.0				pH target 10.5 - actual pH closer to 9.5
24	Settled	1500	9.62	100	2.84	6.8				
	Filtered	1500	9.36	79	0.18	3.4				
						01/09/96				
01/09/96	Raw	815	7.71	102	6.93	32.0		2.4		Ferric Sulfate Dosage (mg/l as liquid) = 30
25	Settled	815	9.22	114	2.97	18.5		2.3		NaOH Dosage (mg/l) = 16
	Filtered	815	9.04	112	0.30	4.1		3.0		
	Raw	1200	8.17	108	99.60	30.0		2.6		Species = As (V)
26	Settled	1200	9.25	114	6.02	11.2		2.3		Notes :
	Filtered	1200	9.09	110	0.21	4.5		1.5		Used filter #1
	Raw	1500	7.50	101	12.90	36.0		2.8		pH target 8.5 - actual pH closer to 9.0
27	Settled	1500	8.70	113	3.38	13.5		2.6		Air and mud from raw water line, thought it was broken.
	Filtered	1500	8.59	106	0.21	4.1		2.4		

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
01/10/96	Raw	900	8.10	----------------	10.30	22.6		2.3		Ferric Sulfate Dosage (mg/l as liquid) = 90
28	Settled	900	8.20	----------------	5.70	4.3		2.3		NaOH Dosage (mg/l) = 20
	Filtered	900	8.10	----------------	1.22	1.0		1.8		
	Raw	1200	8.10	----------------	11.50	22.6		2.9		Species = As (V)
29	Settled	1200	8.20	----------------	3.82	4.3		2.1		Notes :
	Filtered	1200	8.20	----------------	0.34	1.0		2.2		Used filter #3
	Raw	1500	8.12	----------------	8.86	20.1		2.6		pH target 8.5
30	Settled	1500	8.50	----------------	2.58	5.6		2.4		pH meter broken, no titrations possible
	Filtered	1500	8.40	----------------	0.21	2.4		2.3		Pumps started at 500 hours, rather than midnight
						01/11/96				
01/11/96	Raw	900	8.14	107	9.60	27.6		3.1		Ferric Sulfate Dosage (mg/l as liquid) = 30
31	Settled	900	3.72	----------------	9.64	19.8		2.6		Concentrated H2SO4 Dosage (ml/l) = 0.05
	Filtered	900	4.85	3	0.76	2.1		1.2		
	Raw	1200	8.14	----------------	8.75	26.2		2.3		Species = As (V)
32	Settled	1200	3.57	----------------	9.40	18.4		1.1		Notes :
	Filtered	1200	3.70	----------------	0.64	2.4		1.1		Used filter #1
	Raw	1500	8.12	108	8.28	26.0		2.8		pH target 5.0 - actual pH closer to 4.5
33	Settled	1500	4.39	----------------	13.00	18.6		1.1		Filter half full of air when I arrived at 800 hours
	Filtered	1500	4.17	----------------	0.92	1.7		1.0		Foam problem in clear water tanks
						01/12/96				
01/12/96	Raw	900	8.07	108	11.30	29.2		3.4		Ferric Sulfate Dosage (mg/l as liquid) = 60
34	Settled	900	3.86	----------------	10.40	8.5		1.0		Concentrated H2SO4 Dosage (ml/l) = 0.04
	Filtered	900	3.84	----------------	0.16	1.0		1.0		
	Raw	1200	8.07	107	7.34	34.0		2.8		Species = As (V)
35	Settled	1200	5.28	6	9.26	8.1		1.0		Notes :
	Filtered	1200	5.05	2	0.17	1.0		1.0		Used filter #1
	Raw	1500	8.07	108	7.18	31.2		2.6		pH target 5.0 - actual pH varied from 4 to 5 to 6
36	Settled	1500	6.14	27	7.68	14.8		1.2		Chemical doses constant, not sure why pH changed
	Filtered	1500	6.16	28	0.80	1.7		1.0		

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
01/15/96	Raw	900	8.10	108	31.70	29.0		3.0		Ferric Sulfate Dosage (mg/l as liquid) = 90 Concentrated H2SO4 Dosage (ml/l) = 0.03 Species = As (V) Notes : Used filter #3 pH target 5.0 - actual pH closer to 6.5 Raw water source has changed, which may be affecting pH
37	Settled	900	6.28	33	5.25	3.8		1.0		
	Filtered	900	6.44	46	0.24	1.0		1.0		
	Raw	1200	8.07	109	10.40	26.7		3.0		
38	Settled	1200	6.20	29	4.34	3.3		1.0		
	Filtered	1200	6.52	41	0.13	1.0		1.0		
	Raw	1500	8.08	109	9.05	27.2		2.4		
39	Settled	1500	6.20	26	3.70	4.5		1.0		
	Filtered	1500	6.52	40	0.15	1.0		1.0		
01/17/96	Raw	900	8.07	109	11.70	29.4		3.5		Ferric Sulfate Dosage (mg/l as liquid) = 90 Concentrated H2SO4 Dosage (ml/l) = 0.045 Species = As (V) Notes : Used filter #1 pH target 5.0 - actual pH around 6
40	Settled	900	6.16	30	8.36	6.6		1.2		
	Filtered	900	6.29	32	0.31	1.0		1.0		
	Raw	1200	8.09	109	11.10	25.6		3.3		
41	Settled	1200	5.78	15	6.60	3.9		1.2		
	Filtered	1200	5.96	16	0.11	1.0		1.0		
	Raw	1500	8.04	108	10.40	19.0		2.7		
42	Settled	1500	5.21	6	5.27	4.0		1.0		
	Filtered	1500	5.49	6	0.13	1.0		1.0		
01/26/96	Raw	900	8.07	107	14.30	94.7		4.1		Ferric Sulfate Dosage (mg/l as liquid) = 60 Lime Dosage (mg/l) = 90 pH target 10.5 - actual pH around 9.5
43	Settled	900	9.71	41	4.41	9.8		2.7		
	Filtered	900	9.54	38	0.26	5.4		4.5		
01/30/96	Raw	900	8.23	108	13.20	28.8		3.9		Ferric Sulfate Dosage (mg/l as liquid) = 30 Lime Dosage (mg/l) = 180 pH target 10.5 - actual pH around 11.5
44	Settled	900	11.66	202	7.53	2.2	7.6	1.0		
	Filtered	900	11.75	189	0.14	2.7	9.4	1.8		
02/06/96	Raw	900	8.00	107	10.90	21.4		4.9		Ferric Sulfate Dosage (mg/l as liquid) = 60 Lime Dosage (mg/l) = 100 Species = As (V) Notes : Used filter #3 pH target 10.5 - actual pH around 11.0
45	Settled	900	11.03	64	4.84	2.3		1.5		
	Filtered	900	10.93	52	0.18	2.1		1.6		
	Raw	1205	8.14	106	9.98	20.5		4.2		
46	Settled	1205	11.05	70	3.14	1.4		1.4		
	Filtered	1205	10.75	61	0.37	1.1		1.9		
	Raw	1510	8.08	108	11.20	20.4		3.4		
47	Settled	1510	11.41	122	3.22	1.6		1.3		
	Filtered	1510	11.18	106	0.68	1.0		1.4		

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
02/07/96	Raw	900	8.05	108	13.20	27.2		2.8		Ferric Sulfate Dosage (mg/l as liquid) = 90
48	Settled	900	11.00	56	5.64	1.5		2.7		Lime Dosage (mg/l) = 100
	Filtered	900	10.92	51	0.25	2.8		2.4		
	Raw	1230	8.14	106	10.80	28.3		5.1		Species = As (V)
49	Settled	1230	11.03	73	4.91	2.2		2.0		Notes :
	Filtered	1230	11.01	64	0.14	1.1		1.8		Used filter #1
	Raw	1505	8.00	107	10.40	24.6		4.4		pH target 10.5 - actual pH around 11.0
50	Settled	1505	11.19	79	3.41	1.6		2.8		
	Filtered	1505	11.12	75	0.10	1.8		1.7		
02/23/96	Raw	900	7.77	109	19.00	19.8		6.7		Ferric Sulfate Dosage (mg/l as liquid) = 60
51	Settled	900	5.85	23	5.84	4.3		2.7		Concentrated H2SO4 Dosage (ml/l) = 0.04
	Filtered	900	6.05	38	0.40	1.0		1.1		Polymer Dosage (mg/l) = 1.20
	Raw	1205	7.81	108	16.80	18.0		5.5		Species = As (V)
52	Settled	1205	5.75	17	4.57	4.3		2.1		Notes :
	Filtered	1205	6.26	34	0.27	1.0		1.7		Used filter #3
	Raw	1500	7.81	108	17.10	18.2		4.7		pH target 5.0 - actual pH around 6.0
53	Settled	1500	5.61	13	5.91	4.3		2.5		
	Filtered	1500	6.19	31	0.13	1.0		1.0		
02/27/96	Raw	930	7.84	108	15.60	23.0				Ferric Chloride Dosage (mg/l as liquid) = 60
54	Settled	930	5.30	8	6.90	3.5				Concentrated H2SO4 Dosage (ml/l) = 0.046
	Filtered	930	5.42	11	0.11	1.4				Polymer Dosage (mg/l) = 1.20
	Raw	1200	7.50	108	11.10	21.0				Species = As (V)
55	Settled	1200	4.58	1	5.79	3.3				Notes :
	Filtered	1200	5.27	4	0.20	1.2				Used filter #1
	Raw	1510	7.87	108	10.10	32.0		5.0		pH target 5.0
56	Settled	1510	3.83	-	5.71	3.8		1.5		
	Filtered	1510	4.12	-	0.11	1.0		2.0		

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
03/01/96	Raw	915	7.65	109	14.20	28.6		1.0		Ferric Sulfate Dosage (mg/l as liquid) = 60
57	Settled	915	7.29	105	4.44	4.0		1.0		NaOH Dosage (mg/l) = 20
	Filtered	915	7.32	107	0.30	1.0		1.0		Polymer Dosage (mg/l) = 1.20
	Raw	1215	7.60	109	13.70	26.1		1.0		Species = As (V)
58	Settled	1215	7.54	106	2.88	3.3		1.0		Notes :
	Filtered	1215	7.51	105	0.15	1.0		1.0		Used filter #1
	Raw	1515	7.68	110	13.70	19.8		1.0		pH target 8.5 - actual pH around 7.5
59	Settled	1515	7.47	104	2.67	3.3		1.0		
	Filtered	1515	7.56	106	0.19	1.5		1.0		
03/07/96	Raw	900	7.80	110	13.90	25.4		10.4		Ferric Chloride Dosage (mg/l as liquid) = 60
60	Settled	900	7.82	106	3.54	2.6		1.0		NaOH Dosage (mg/l) = 28
	Filtered	900	7.50	106	0.26	1.0		1.0		Polymer Dosage (mg/l) = 1.20
	Raw	1210	7.67	109	13.80	25.9		1.0		Species = As (V)
61	Settled	1210	7.73	108	2.43	3.2		1.0		Notes :
	Filtered	1210	7.73	107	0.16	1.0		1.0		Used filter #1
	Raw	1500	7.73	111	13.00	23.6		1.0		pH target 8.5 - actual pH around 7.5
62	Settled	1500	7.90	109	2.71	3.5		1.0		
	Filtered	1500	7.84	108	0.18	1.1		1.0		
03/12/96	Raw	910	7.46	107	13.60	23.8				Ferric Chloride Dosage (mg/l as liquid) = 46
63	Settled	910	5.88	27	5.66	3.2				Concentrated H2SO4 Dosage (ml/l) = 0.037
	Filtered	910	6.25	26	0.60	1.0				Raw water shut-off at 10:30 by plant personnel accidently.

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity mg/L as CaCO3	Turbidity NTU	Arsenic Total ug/L	Arsenic Dissolved ug/L	Organic Carbon Total mg/L	Organic Carbon Dissolved mg/L	Remark
1	2	3	4	5	1	2	3	4.0	5	12
03/13/96	Raw	900	7.59	106	13.60	19.0		4.7		Ferric Chloride Dosage (mg/l as liquid) = 46 Concentrated H2SO4 Dosage (ml/l) = 0.040 Species = As (V) Notes : Used filter #3 pH target 5.0 - actual pH around 6.0
64	Settled	900	5.74	17	5.85	3.5		1.8		
	Filtered	900	6.04	31	0.54	1.0		1.0		
	Raw	1210	7.67	106	13.20	19.5				
65	Settled	1210	5.45	9	5.00	2.8				
	Filtered	1210	6.24	25	0.18	1.0				
	Raw	1515	7.66	108	13.50	19.8				
66	Settled	1515	5.35	7	5.19	5.0				
	Filtered	1515	5.92	23	0.12	1.0				
03/19/96	Raw	930	7.54	108	19.80	28.5				Ferric Chloride Dosage (mg/l as liquid) = 46 Concentrated H2SO4 Dosage (ml/l) = 0.044 Ozone dose = 1% wt/wt @ 35scfh Species = As (V) Notes : Used filter #3 pH target 5.0 - actual pH around 6.0
67	Settled	930	5.43	8	8.10	3.2				
	Filtered	930	5.87	22	0.16	1.0				
	Raw	1230	7.61	107	16.00	24.8				
68	Settled	1230	4.32	----------	7.39	5.4				
	Filtered	1230	6.15	18	0.25	1.0				
	Raw	1500	7.64	108	16.10	25.0				
69	Settled	1500	4.03	----------	6.07	5.2				
	Filtered	1500	6.07	17	0.13	1.0				
03/22/96	Raw	900	7.70	108	19.10	24.5				Ferric Sulfate Dosage (mg/l as liquid) = 60 Concentrated H2SO4 Dosage (ml/l) = 0.040 Ozone dose = 1% wt/wt @ 35scfh Species = As (V) Notes : Used filter #1 pH target 5.0 Floculators not set properly
70	Settled	900	5.82	17	7.02	3.8				
	Filtered	900	5.82	19	1.26	1.0				
	Raw	1210	7.59	107	15.40	40.0				
71	Settled	1210	5.37	8	5.93	5.8				
	Filtered	1210	5.83	10	0.55	1.0	<5			
	Raw	1600	7.65	108	13.00	3.3				
72	Settled	1600	4.62	1	5.22	3.3				
	Filtered	1600	5.03	2	0.30	1.0				

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
03/26/96	Raw	1000	7.58	107	4.90	19.7				
73	Settled	1000	5.50	9	6.73	4.1				Ferric Sulfate Dosage (mg/l as liquid) = 60
	Filtered	1000	6.37	10	0.28	1.0				Concentrated H2SO4 Dosage (ml/l) = 0.040
	Raw	1300	7.50	106	11.90	17.9				Polymer Dose (mg/l) = 1.20
74	Settled	1300	4.56	----------	5.93	5.0				Ozone dose = 1% wt/wt @ 35scfh
	Filtered	1300	4.88	2	0.25	1.0				Species = As (V)
	Raw	1500	7.54	106	11.30	18.6				Notes :
75	Settled	1500	4.26	----------	4.65	4.0				Used filter #1
	Filtered	1500	4.61	2	0.33	1.0				pH target 5.0
03/29/96	Raw	900	7.56	107	15.20	26.4				
76	Settled	900	5.65	13	6.96	4.7				Ferric Chloride Dosage (mg/l as liquid) = 46
	Filtered	900	5.81	14	0.21	1.0				Concentrated H2SO4 Dosage (ml/l) = 0.044
	Raw	1200	7.62	108	13.40	28.4				Polymer Dose (mg/l) = 1.20
77	Settled	1200	5.00	3	5.86	3.1				Ozone dose = 1% wt/wt @ 35scfh
	Filtered	1200	5.52	5	0.34	1.0				Species = As (V)
	Raw	1400	7.62	107	13.20	26.6				Notes :
78	Settled	1400	4.25	----------	5.33	5.2				Used filter #1
	Filtered	1400	4.72	1	0.35	1.0				pH target 5.0
04/23/96	Raw	900	7.89	108	13.90	23.4		3.8		
79	Settled	900	8.88	108	2.83	3.5		3.2		Ferric Sulfate Dosage (mg/l as liquid) = 60
	Filtered	900	8.69	100	0.36	1.2		3.0		NaOH Dosage (mg/l) = 35
	Raw	1200	7.90	108	13.30	25.0		3.6		Ozone dose = 1% wt/wt @ 35scfh
80	Settled	1200	9.15	116	4.33	5.7		3.0		
	Filtered	1200	8.81	96	0.13	2.4		2.9	Reruns	Species = As (V)
	Raw	1500	7.80	108	14.00	26.6		3.8	4.10	Notes :
81	Settled	1500	9.09	108	3.68	6.5		3.0	3.24	Used filter #3
	Filtered	1500	8.74	92	0.10	1.0		2.9	3.30	pH target 8.5

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
04/30/96	Raw	900	7.94	118	10.70	34.5		3.9		Ferric Chloride Dosage (mg/l as liquid) = 46
91	Settled	900	8.74	116	3.65	3.9		3.3		NaOH Dosage (mg/l) = 28
	Filtered	900	8.56	112	0.45	1.7		3.2		
	Raw	1210	7.97	117	9.82	21.6		3.9		
92	Settled	1210	8.82	112	3.22	4.6		3.3		Species = As (V)
	Filtered	1210	8.54	106	0.23	1.2		3.2		Notes :
	Raw	1500	7.92	117	10.20	25.7		4.0		Used filter #1
93	Settled	1500	8.80	113	3.17	3.9		3.3		pH target 8.5
	Filtered	1500	8.46	103	0.21	1.1		3.2		
05/01/96	Raw	920	7.89	112	11.10	13.6		4.0		Ferric Chloride Dosage (mg/l as liquid) = 46
94	Settled	920	8.67	114	1.92	1.0		2.9		NaOH Dosage (mg/l) = 28
	Filtered	920	8.47	107	0.28	1.0		3.1		Polymer Dose (mg/l) = 1.20
	Raw	1200	7.83	110	11.00	11.6		3.7		Ozone dose = 1% wt/wt @ 35scfh
95	Settled	1200	8.80	110	2.66	2.2		3.0		Species = As (III)
	Filtered	1200	8.50	104	0.13	1.0		2.8		Notes :
	Raw	1500	7.84	115	10.70	12.8		3.9		Used filter #3
96	Settled	1500	8.81	111	2.19	1.5		2.8		pH target 8.5
	Filtered	1500	8.41	100	0.10	1.0		2.8		First run with Arsenic (III) since first week of testing
05/02/96	Raw	930	7.80	106	11.20	13.0		3.7		Ferric Sulfate Dosage (mg/l as liquid) = 60
97	Settled	930	8.85	108	2.47	2.7		2.7		NaOH Dosage (mg/l) = 28
	Filtered	930	8.73	104	0.16	1.0		2.9		Polymer Dose (mg/l) = 1.20
	Raw	1200	7.81	105	13.20	11.2		3.7		Ozone dose = 1% wt/wt @ 35scfh
98	Settled	1200	8.94	107	2.49	1.8		2.6		Species = As (III)
	Filtered	1200	8.71	100	0.11	1.0		2.6		Notes :
	Raw	1500	7.76	104	12.10	11.8		3.9		Used filter #1
99	Settled	1500	8.96	104	2.67	1.7		2.7		pH target 8.5
	Filtered	1500	8.68	96	0.12	1.0		2.7		

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study **Job Code :** CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
05/10/96	Raw	900	7.74	105	9.72	8.4		4.0		Ferric Chloride Dosage (mg/l as liquid) = 46
109	Settled	900	8.84	104	2.44	3.0		3.1		NaOH Dosage (mg/l) = 28
	Filtered	900	8.50	94	0.18	1.3		3.0		Polymer Dose (mg/l) = 1.20
	Raw	1210	7.66	103	9.28	9.1		3.7		
110	Settled	1210	8.97	99	2.70	2.2		2.9		Species = As (III)
	Filtered	1210	8.55	88	0.19	1.0		3.0		Notes :
	Raw	1500	7.71	104	9.31	9.4		4.2		Used filter #3
111	Settled	1500	9.15	96	1.90	3.5		3.1		pH target 8.5
	Filtered	1500	8.77	84	0.13	1.7		3.1		Last run with As (III)
05/15/96	Raw	930	7.76	108	8.32	45.2		3.8		Ferric Chloride Dosage (mg/l as liquid) = 46
112	Settled	930	8.76	109	2.66	4.4		2.9		NaOH Dosage (mg/l) = 28
	Filtered	930	8.40	102	0.47	1.8		2.9		Polymer Dose (mg/l) = 1.20
	Raw	1200	7.70	106	9.28	47.2		3.6		
113	Settled	1200	8.80	106	3.02	5.9		2.8		Species = As (V)
	Filtered	1200	8.43	96	0.18	1.0		2.8		Notes :
	Raw	1500	7.68	102	14.3	26.0		3.6		Used filter #3
114	Settled	1500	8.78	101	2.85	6.9		2.8		pH target 8.5
	Filtered	1500	8.47	92	0.17	1.0		2.7		

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
05/03/96	Raw	930	7.81	110	11.20	12.2		3.8		Ferric Chloride Dosage (mg/l as liquid) = 46
100	Settled	930	8.74	112	2.81	1.6		4.2		NaOH Dosage (mg/l) = 28
	Filtered	930	8.48	105	0.25	1.0		3.0		
	Raw	1200	7.78	107	9.72	12.2		4.2		
101	Settled	1200	8.79	107	2.53	1.8		3.0		Species = As (III)
	Filtered	1200	8.47	96	0.26	1.0		3.2		Notes :
	Raw	1500	7.85	108	9.85	13.5		4.0		Used filter #1
102	Settled	1500	8.83	103	3.05	2.8		3.1		pH target 8.5
	Filtered	1500	8.46	95	0.19	1.2		3.1		
05/08/96	Raw	900	7.77	111	9.47	9.5		3.6		Ferric Sulfate Dosage (mg/l as liquid) = 60
103	Settled	900	8.59	112	2.51	1.7		3.3		NaOH Dosage (mg/l) = 27
	Filtered	900	8.41	108	0.56	1.2		3.3		
	Raw	1200	7.68	108	9.57	10.4		3.9		
104	Settled	1200	8.69	108	3.63	2.7		3.1		Species = As (III)
	Filtered	1200	8.45	103	0.27	1.6		3.1		Notes :
	Raw	1500	7.71	110	9.53	10.7		3.6		Used filter #3
105	Settled	1500	8.76	108	3.74	3.1		3.1		pH target 8.5
	Filtered	1500	8.42	100	0.24	1.1		3.1		
05/09/96	Raw	930	7.81	110	10.00	10.6		3.9		Ferric Sulfate Dosage (mg/l as liquid) = 60
106	Settled	930	8.81	108	2.63	3.0		3.0		NaOH Dosage (mg/l) = 28
	Filtered	930	8.56	102	0.20	1.7		2.9		Polymer Dose (mg/l) = 1.20
	Raw	1200	7.75	109	9.78	10.6		3.8		
107	Settled	1200	8.85	106	2.95	3.0		2.9		Species = As (III)
	Filtered	1200	8.54	100	0.10	1.5		3.0		Notes :
	Raw	1500	7.74	109	9.68	10.0		3.6		Used filter #1
108	Settled	1500	8.83	104	2.41	3.7		3.0		pH target 8.5
	Filtered	1500	8.51	96	0.15	1.6		2.9		

SUMMARY OF PILOT PLANT TEST RESULTS

07/24/96

Project : Arsenic Removal Study

Job Code : CFW 9513

Test Date	Sample Location/ Code	Sample Time	Final pH	Total Alkalinity	Turbidity	Arsenic		Organic Carbon		Remark
						Total	Dissolved	Total	Dissolved	
				mg/L as CaCO3	NTU	ug/L		mg/L		
1	2	3	4	5	1	2	3	4.0	5	12
04/24/96	Raw	930	8.01	110	12.90	33.6		3.7		Ferric Sulfate Dosage (mg/l as liquid) = 60 NaOH Dosage (mg/l) = 31 Polymer Dose (mg/l) = 1.20 Ozone dose = 1% wt/wt @ 35scfh Species = As (V) Notes : Used filter #1 pH target 8.5
82	Settled	930	8.81	111	2.36	3.6		2.9		
	Filtered	930	8.71	109	0.26	1.3		2.9		
	Raw	1200	7.86	108	12.00	35.2		7.7	Rerun	
83	Settled	1200	9.02	110	2.85	3.8		2.9		
	Filtered	1200	8.83	104	0.19	2.2		2.9		
	Raw	1500	7.84	109	12.30	31.8		3.7		
84	Settled	1500	9.02	107	2.44	7.4		2.9		
	Filtered	1500	8.75	100	0.11	4.4		2.9		
04/25/96	Raw	900	7.82	109	17.20	30.0		3.6		Ferric Chloride Dosage (mg/l as liquid) = 46 NaOH Dosage (mg/l) = 28 Ozone dose = 1% wt/wt @ 35scfh Species = As (V) Notes : Used filter #1 pH target 8.5
85	Settled	900	8.72	111	2.37	3.6		2.7		
	Filtered	900	8.67	108	0.16	1.0		3.0		
	Raw	1200	7.85	109	12.10	29.3		3.7		
86	Settled	1200	8.75	111	2.72	4.6		3.0		
	Filtered	1200	8.59	104	0.10	1.7		2.7		
	Raw	1500	7.89	114	12.50	25.0		3.9		
87	Settled	1500	8.78	110	3.23	5.7		2.9		
	Filtered	1500	8.59	102	0.11	1.0		2.9		
04/26/96	Raw	1000	8.14	116	12.70	24.2		3.6		Ferric Chloride Dosage (mg/l as liquid) = 46 NaOH Dosage (mg/l) = 28 Polymer Dose (mg/l) = 1.20 Ozone dose = 1% wt/wt @ 35scfh Species = As (V) Notes : Used filter #3 pH target 8.5
88	Settled	1000	8.77	116	2.65	6.0		2.6		
	Filtered	1000	8.59	108	0.16	1.3		2.6		
	Raw	1200	7.91	116	13.80	24.2		3.8		
89	Settled	1200	8.82	115	3.37	4.2		3.0		
	Filtered	1200	8.47	105	0.09	1.9		2.8		
	Raw	1500	7.91	116	13.20	25.0		3.9		
90	Settled	1500	8.80	113	3.39	2.8		3.0		
	Filtered	1500	8.43	103	0.14	2.0		2.6		